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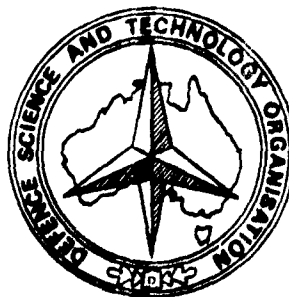DEFENCE RESEARCH CENTRE SALISBURY
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TECHNICAL REPORT

WSRL-0090-TR

WIND TUNNEL TESTS ON THE STATIC AERODYNAMICS OF
A SPINNING 105 MM ARTILLERY SHELL MODEL

C. JERMEY

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S U M M A R Y

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The aerodynamic characteristics of a spinning 105 mm shell shape have been measured as a prelude to tests of a shell shape fitted with canard control surfaces.   Tests were conducted at incidences of zero to 15°, and Mach numbers of 0.70 to 0.95 and 1.4.   Results indicate that the use of canard surfaces to control the flight path of such a projectile is unlikely to be very effective within the low transonic Mach number range, but could possibly be effective in supersonic flight.

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1. INTRODUCTION

The work reported here was conducted as a preliminary step in a program to assess the feasibility of using canard controls on a spinning projectile to control its flight path, and hence its point of impact.   The projectile shape chosen was the 105 mm H.E. M1 shell with M557 P.D. fuse and the tests were designed to provide a data bank for comparison with later tests of a canard equipped shell shape.   The test programme also provided the opportunity to develop the equipment and techniques needed for this type of work.

The basic equipment for the wind tunnel testing of rapidly spinning models already existed as a result of a Magnus research project some years earlier, and this equipment was modified as necessary to accommodate the new model and new data requirements.   The tests were carried out during September and November of 1977, and since no significant problems occurred, considerable confidence was gained in the equipment and techniques used.

2. EXPERIMENTAL DETAILS

2.1 Model and balance

The model used was a half scale model of the 105 mm H.E. M1 shell, fitted with an M557 P.D. fuse.   Production drawings were used for all dimensions, except for details of the drive band, which were obtained by direct measurement from a fired shell.

Figures 1 and 2 show the model and the balance assembled, figure 1 showing the internal details of the drive and roll rate measuring system.   In figure 2 it may be seen that the direction of the rifling grooves on the drive band is opposite to that on the full size shell.   This is because the roll drive motor operates only in the opposite sense to the rotation of the full size shell.   Consequently, all roll rates in this report are negative and Magnus forces and moments are of opposite sign to those existing on the full size shell.

The model was mounted onto the shaft of a sliding-vane type air motor, which incorporates an air-bearing for low friction radial support, and this then fitted onto the end of a strain gauge sting balance.   The high pressure air for the motor was supplied through the hollow core of the balance, and the low pressure air for the air-bearing through two thin tubes taped to the outside of the sting.   The roll rate of the model was monitored by a "hall effect" sensor, mounted on the sting and triggered once each revolution by a small magnet on the model.   Control of the roll rate was effected by varying the pressure of the air supply to the motor.

Since spin rates of up to 330 r/s were required, careful dynamic balancing of the model was necessary before commencing wind tunnel testing.   This was accomplished outside the tunnel with the model mounted on the strain gauge balance and the balance outputs monitored on a CRO screen.   Observation of the amplitude and phase of the outputs as the model was spun enabled the positioning of small masses on the outside of the model to compensate for the imbalance observed.   These balancing masses were then translated into internal masses, which were fitted, and then the model spun again as a check. Excellent balance was obtained, with only one fairly "noisy" resonant area at about 125 r/s, corresponding to oscillation about the front cage of the balance.   This spin rate was therefore avoided where possible during the wind tunnel tests.

2.2 Experimental procedure

All tests reported here were carried out in the 360 mm x 380 mm slotted working section of the continuous flow wind tunnel S-1 at the Aeroballistics Division of WSRL.   Data were obtained for the subsonic Mach number range of 0.70 to 0.95 and also at a Mach number of 1.4.

A Reynolds number of $R_d = 3.9 \times 10^5$ (based on maximum body diameter) was used throughout the tests, this being the highest Reynolds number attainable for the complete range of Mach numbers without overloading the balance.   This compares with flight Reynolds numbers which are typically 1.0 to 2.0 x 10^6. A boundary layer trip, shown and described in figure 1, was included to ensure a turbulent boundary layer over the shell body, to simulate flow conditions expected at the higher Reynolds numbers of the full scale shell.

The experimental procedure consisted of establishing the required tunnel flow conditions, setting the required model roll rate by adjusting the motor supply pressure, and then conducting a pitch traverse of the model from -4° to 15°, taking data at one degree intervals.   For the tests at zero roll rate it was found necessary to shut off the air supply to the model air bearing, otherwise the torque generated by the grooves of the driving band was sufficient to produce a small steady roll rate.   With no air supplied, the friction between the air bearing surfaces prevented the model from rolling. For consistency, all non-rolling tests were conducted at a constant roll orientation, chosen to be with the fuse delay adjustment screw hole on the windward streamline.   Brief tests at other roll orientations, however, showed no discernible differences in the measured forces and moments.

2.3 Accuracy of results

The results consist of aerodynamic force and moment coefficients at given Mach numbers, Reynolds number, incidences and roll rates.   The sources of error and the accuracy applicable to each item are discussed below.

(a) Force and moment coefficients

These were obtained from the electrical outputs of the strain gauges on the sting balance.   The major sources of error are in the balance calibration and the dynamic effects of the spinning model, i.e., vibration and the discharge of exhaust air.   Under static conditions the balance is capable of measuring forces and moments to an accuracy of 0.1%.   No attempt was made to calibrate the balance under dynamic conditions, but comparison of spinning and non-spinning tests with no tunnel flow indicated that discrepancies were small, generally less than 0.5%.   A reasonable estimate of the maximum percentage uncertainty in the force and moment coefficients would therefore be 1%.

An absolute uncertainty also exists in each force and moment coefficient, arising mainly from the resolution limits of the measuring system, balance temperature changes, and noise levels in the balance outputs.   This uncertainty is variable with Mach number and incidence, but is of a maximum order of 0.01 for all coefficients.

(b) Mach numbers

The Mach number is manually controlled from observation of the stagnation pressure in the settling chamber and the static pressure in the working section.   Mach numbers are held to within 0.01 of the nominal figure, and this is also the level of spatial uncertainty in the centreline Mach number of the working section.   No corrections have been applied for the effects of blockage.

(c) Reynolds number

The Reynolds number is derived from the Mach number and stagnation temperature of the air flow, and since the stagnation temperature varies somewhat during a tunnel run, the Reynolds number varies correspondingly.   For all tests reported here the Reynolds number was within the range $(3.9 \pm 0.1) \times 10^5$.

(d) Incidence

   The combined effect of errors in support attitude measurement and
   sting bending corrections produces an uncertainty in attitude measure-
   ment of less than 0.01^{o}.   However, airflow direction on the tunnel
   axis is uniform only to within 0.2^{o}, so that this is a more realistic
   estimate of the uncertainty in the incidences quoted.

(e) Roll rate

   Roll rates were obtained by using a counter to display the total
   number of pulses received each second from the model, which generated
   one pulse per revolution.   All data were taken only after the model
   had reached a steady roll rate, although small changes inevitably
   occurred as the incidence was varied during a run.   The roll rate
   given for each data point is therefore accurate to within 1 r/s
   (6 rad/s), but the approximate roll rates for an entire run may have
   uncertainties of up to 3 r/s (19 rad/s).

3.   PRESENTATION AND DISCUSSION OF RESULTS

3.1 Presentation of results

   Results are presented in tabular form as Tables 1 to 7, and also in graphi-
cal form as figures 4 to 10, where selected results have been plotted to
illustrate trends as a function of incidence, Mach number and roll rate.
Figure 3 shows the axis system used throughout, the origin of the system
being positioned at the nominal centre of gravity of the shell, i.e., 2.97
calibers from the nose tip.
   The tabular data are presented as 'raw' computer output, and so must be
interpreted with some care.   In particular, centres of pressure are derived
from the division of a moment coefficient by a force coefficient, and so are
subject to large errors as the force approaches zero.
   Figures 4 and 5 show that normal force and pitching moment are continuous
functions of incidence up to 15° for all Mach numbers, indicating that no
sudden changes occur in the cross-flow pattern within this range.   Also of
interest is that spin rate has very little effect on the normal force and
pitching moment.   This is further illustrated in figure 6, where normal
force and pitching moment are plotted against non-dimensional spin rate

$(p' = \frac{pd}{2U_{\infty}})$ for various Mach numbers and incidences (typical flight values of

non-dimensional spin rate are within the range 0.14 to 0.20).   The centre
of pressure in the pitch plane is plotted in figure 7, which shows that for
subsonic conditions, increasing spin rate tends to bring the centre of press-
ure back from the nose, especially at lower incidences.   Figure 7 also shows
that the subsonic centre of pressure is well forward, generally less than one
caliber from the nose, and in some cases even ahead of the nose.   The centre
of pressure also varies considerably with Mach number and incidence, being
furthest forward for transonic and low incidence conditions.   The supersonic
centre of pressure is further back (approximately 1½ calibers from the nose)
and is less variable with incidence and spin rate.
   Figure 8 shows the effect of incidence, Mach number and spin rate on the
side (Magnus) force coefficient.   In general it shows a relatively linear
increase with increasing incidence and spin rate, though with some scatter,
thought to be due mainly to the difficulty of measuring the relatively small
forces involved.   However, at transonic conditions this linearity is lost
at the higher incidences, where increasing incidence reduces the side force
and may even reverse its direction.

Figure 9 shows the yawing (Magnus) moment coefficient and its variation
with incidence, Mach number and roll rate.   The proximity of the yaw plane
centre of pressure to the origin of the axis system results in the yawing
moments being very small, generally of a similar order to the level of uncer-
tainty in their measurement (0.01).   Trends are therefore largely submerged
in the noise level except for high subsonic conditions (Mach 0.9 and 0.95)
where the non-linearity of the Magnus effects with incidence is again evident.

Figure 10 shows the variation of the force and moment coefficient deriva-
tives with Mach number (at zero incidence).   Generally speaking, they show
the tendency of relatively gradual change at moderate subsonic speeds, more
rapid change at transonic speeds leading to extreme values, and a return to
more moderate values at supersonic speed.   As has already been noted, the
aerodynamic characteristics of the shell shape are significantly non-linear
at high incidence, and so the derivatives given in figure 10 are valid only
at low incidence, i.e., less than 5°.

3.2 Implications for the use of canard controls

Results indicate that the use of canard surfaces to control the attitude
and hence the flight path of a 105 mm shell is unlikely to be very effective
within the transonic Mach number range.   This is because the centre of
pressure in the pitch plane is situated very close to the likely canard
position, and is highly variable with variations in Mach number, incidence
and spin rate.   The canard normal force required to produce trim at inci-
dence will therefore be almost equal and opposite to the body normal force,
and so the resultant normal force at trim is likely to be small and highly
variable with Mach number, incidence and spin rate.   Side (Magnus) forces
are also small and are non-linear at high incidence and high Mach number.

Canard controls could possibly be effective in supersonic flight since
the centre of pressure is then further back along the body and much less
sensitive to variations in incidence and spin rate.

NOTATION

C_Z	normal force coefficient $= \dfrac{Z}{qS}$
C_Y	side force coefficient $= \dfrac{Y}{qS}$
C_m	pitching moment coefficient $= \dfrac{m}{qSd}$
C_n	yawing moment coefficient $= \dfrac{n}{qSd}$
$C.P._Z$	position of centre of pressure in the pitch plane, forward of cg is +ve
$C.P._y$	position of centre of pressure in the yaw plane, forward of cg is +ve
C_{Z_α}	derivative of normal force coefficient with respect to incidence $= \partial C_Z / \partial \alpha$
C_{m_α}	derivative of pitching moment coefficient with respect to incidence $= \partial C_m / \partial \alpha$
$C_{Y_{p\alpha}}$	double derivative of side force coefficient with respect to roll rate and incidence $= \partial^2 C_y / \partial p' . \partial \alpha$
$C_{n_{p\alpha}}$	double derivative of yawing moment coefficient with respect to roll rate and incidence $= \partial^2 C_n / \partial p' . \partial \alpha$
M	Mach number of free stream
R_d	Reynolds number of free stream, based on maximum body diameter
S	maximum body cross sectional area
U_∞	velocity of free stream
Y	side force
Z	normal force
d	maximum body diameter
m	pitching moment
n	yawing moment
p	roll rate; clockwise from rear is +ve
p'	non-dimensional roll rate $= \dfrac{pd}{2 U_\infty}$
q	dynamic pressure of free stream
α	incidence angle relative to free stream

TABLE 1. AERODYNAMIC COEFFICIENTS, M = 0.70

$a°$	$C.P._z$	C_Y	C_Z	C_m	C_n	$C.P._y$	p(rad/s)	p'
-3.93	2.573	0.003	0.102	-0.263	-0.001	-0.41	0.-0.0000	
-2.92	2.605	0.003	0.073	-0.101	-0.001	-0.31	0.-0.0000	
-1.92	2.671	0.002	0.045	-0.120	-0.000	-0.12	0.-0.0000	
-0.92	2.608	0.002	0.018	-0.048	0.000	0.14	0.-0.0000	
0.09	2.456	0.002	-0.011	0.026	0.001	0.57	0.-0.0000	
1.09	2.521	0.002	-0.039	0.098	0.001	0.84	0.-0.0000	
2.11	2.546	0.001	-0.058	0.172	0.002	1.48	0.-0.0000	
3.11	2.563	0.001	-0.095	0.242	0.002	1.84	0.-0.0000	
4.10	2.523	0.001	-0.125	0.314	0.002	2.43	0.-0.0000·	
5.11	2.466	0.001	-0.156	0.384	0.003	3.75	0.-0.0000	
6.15	2.434	0.001	-0.187	0.455	0.003	5.69	0.-0.0000	
7.13	2.304	0.000	-0.219	0.524	0.003	7.96	0.-0.0000·	
8.15	2.350	0.000	-0.253	0.594	0.004	17.71	0.-0.0000	
9.15	2.300	0.000	-0.287	0.661	0.004	54.10	0.-0.0000	
10.15	2.253	-0.000	-0.322	0.726	0.004	-14.64	0.-0.0000	
11.17	2.192	0.000	-0.362	0.793	0.005	26.33	0.-0.0000	
12.17	2.132	-0.000	-0.402	0.856	0.004	-7.85	0.-0.0000	
13.19	2.066	-0.000	-0.445	0.919	0.003	-7.67	0.-0.0000	
14.21	1.991	-0.001	-0.492	0.979	0.003	-2.17	0.-0.0000	
15.19	1.910	-0.003	-0.539	1.034	0.004	-1.22	0.-0.0000	

(a) p = o

$a°$	$C.P._z$	C_Y	C_Z	C_m	C_n	$C.P._y$	p(rad/s)	p'
-3.92	2.644	-0.006	0.100	-0.265	0.015	-2.73	-942.-0.1029	
-2.91	2.760	-0.011	0.070	-0.192	0.009	-0.83	-936.-0.1022	
-1.90	2.826	-0.005	0.043	-0.121	0.011	-2.37	-942.-0.1029	
-0.89	3.173	-0.003	0.015	-0.048	0.010	-2.89	-936.-0.1022	
0.10	1.786	0.001	-0.013	0.023	0.011	12.88	-936.-0.1022	
1.12	2.339	0.002	-0.042	0.099	0.009	5.49	-936.-0.1020	
2.13	2.456	0.008	-0.070	0.172	0.011	1.42	-936.-0.1020	
3.14	2.488	0.010	-0.097	0.242	0.010	0.98	-930.-0.1015	
4.15	2.454	0.012	-0.127	0.312	0.008	0.71	-930.-0.1013	
5.15	2.412	0.014	-0.158	0.381	0.008	0.55	-936.-0.1020	
6.17	2.373	0.015	-0.191	0.452	0.005	0.36	-936.-0.1020	
7.18	2.334	0.017	-0.224	0.522	0.003	0.18	-936.-0.1020	
8.18	2.291	0.024	-0.257	0.589	0.005	0.22	-949.-0.1034	
9.19	2.254	0.026	-0.292	0.657	0.001	0.05	-942.-0.1027	
10.20	2.202	0.027	-0.327	0.721	0.000	0.01	-949.-0.1034	
11.21	2.161	0.032	-0.364	0.787	0.005	0.16	-949.-0.1034	
12.22	2.106	0.032	-0.404	0.851	0.007	0.22	-955.-0.1041	
13.22	2.035	0.033	-0.448	0.912	0.006	0.20	-955.-0.1041	
14.24	1.964	0.039	-0.495	0.971	0.010	0.25	-955.-0.1041	
15.24	1.891	0.035	-0.544	1.030	0.007	0.19	-955.-0.1041	

(b) p ≈ -150 rev/s

TABLE 1(CONTD.).

a^o	C.P.$_Z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-3.92	2.832	-0.015	0.093	-0.264	0.017	-1.15	-1565.	-0.1705
-2.91	2.935	-0.006	0.066	-0.194	0.019	-2.35	-1565.	-0.1705
-1.90	3.179	-0.006	0.038	-0.121	0.017	-2.82	-1571.	-0.1712
-0.89	5.097	-0.004	0.010	-0.049	0.013	-3.35	-1571.	-0.1712
0.10	1.280	-0.001	-0.017	0.022	0.012	-17.56	-1565.	-0.1705
1.12	2.090	-0.000	-0.045	0.094	0.009	-22.75	-1565.	-0.1705
2.13	2.270	0.005	-0.074	0.168	0.008	1.52	-1565.	-0.1705
3.15	2.347	0.011	-0.102	0.240	0.008	0.73	-1565.	-0.1705
4.15	2.377	0.015	-0.131	0.311	0.004	0.28	-1565.	-0.1705
5.15	2.373	0.021	-0.161	0.382	0.004	0.21	-1558.	-0.1698
6.17	2.311	0.029	-0.196	0.453	0.005	0.16	-1558.	-0.1698
7.18	2.274	0.036	-0.229	0.520	0.004	0.12	-1558.	-0.1698
8.18	2.223	0.034	-0.263	0.584	-0.002	-0.06	-1565.	-0.1705
9.19	2.184	0.046	-0.299	0.653	0.003	0.07	-1565.	-0.1705
10.20	2.134	0.044	-0.336	0.717	-0.003	-0.06	-1565.	-0.1705
11.21	2.082	0.051	-0.376	0.783	-0.000	-0.01	-1558.	-0.1698
12.22	2.043	0.055	-0.414	0.846	-0.004	-0.06	-1565.	-0.1702
13.22	1.974	0.060	-0.458	0.904	0.003	0.05	-1565.	-0.1702
14.24	1.907	0.063	-0.504	0.961	0.005	0.08	-1565.	-0.1702
15.24	1.838	0.067	-0.555	1.021	0.008	0.11	-1565.	-0.1705

(c) $p \approx -249$ rev/s

TABLE 2.   AERODYNAMIC COEFFICIENTS, M = 0.75

α°	C.P.$_z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-3.95	2.592	0.002	0.103	-0.268	-0.001	-0.32	0.-0.0000	
-2.95	2.616	0.002	0.076	-0.197	-0.000	-0.01	0.-0.0000	
-1.93	2.640	0.002	0.046	-0.123	0.001	0.41	0.-0.0000	
-0.93	2.594	0.001	0.019	-0.049	0.001	1.02	0.-0.0000	
0.07	2.717	0.001	-0.009	0.024	0.002	2.07	0.-0.0000	
1.08	2.670	0.001	-0.037	0.099	0.003	3.57	0.-0.0000	
2.10	2.659	0.000	-0.065	0.173	0.003	7.99	0.-0.0000·	
3.12	2.637	0.000	-0.093	0.245	0.003	8.05	0.-0.0000·	
4.09	2.601	-0.000	-0.120	0.313	0.004	-16.36	0.-0.0000	
5.11	2.539	-0.000	-0.153	0.388	0.004	-13.09	0.-0.0000	
6.13	2.496	-0.000	-0.184	0.458	0.004	-12.40	0.-0.0000	
7.13	2.443	-0.001	-0.216	0.528	0.005	-8.76	0.-0.0000	
8.15	2.395	-0.001	-0.250	0.598	0.005	-6.89	0.-0.0000	
9.15	2.345	-0.001	-0.284	0.665	0.005	-5.51	0.-0.0000	
10.15	2.291	-0.002	-0.320	0.733	0.006	-3.70	0.-0.0000	
11.18	2.225	-0.001	-0.359	0.799	0.006	-6.30	0.-0.0000	
12.18	2.162	-0.002	-0.399	0.862	0.005	-3.08	0.-0.0000	
13.18	2.092	-0.003	-0.443	0.927	0.003	-1.13	0.-0.0000·	
14.20	2.015	-0.001	-0.489	0.985	0.004	-5.95	0.-0.0000	
15.21	1.936	-0.002	-0.540	1.047	0.005	-2.14	0.-0.0000	

(a) p = o

α°	C.P.$_z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-3.95	2.636	-0.005	0.103	-0.271	0.013	-2.46	-936.	-0.0960
-2.95	2.699	-0.008	0.074	-0.200	0.008	-0.95	-942.	-0.0966
-1.93	2.831	-0.002	0.045	-0.126	0.011	-6.42	-942.	-0.0966
-0.93	3.051	-0.002	0.018	-0.055	0.010	-6.32	-942.	-0.0966
0.07	1.706	-0.001	-0.011	0.019	0.007	-5.96	-949.	-0.0973
1.08	2.357	0.000	-0.040	0.094	0.006	104.11	-949.	-0.0973
2.10	2.455	0.005	-0.068	0.168	0.008	1.45	-942.	-0.0966
3.13	2.460	0.005	-0.099	0.243	0.004	0.86	-955.	-0.0979
4.11	2.441	0.011	-0.127	0.311	0.006	0.50	-961.	-0.0986
5.13	2.329	0.014	-0.160	0.382	0.004	0.31	-955.	-0.0979
6.13	2.360	0.015	-0.192	0.454	0.004	0.26	-949.	-0.0973
7.14	2.327	0.020	-0.226	0.525	0.001	0.05	-955.	-0.0979
8.15	2.286	0.020	-0.259	0.592	-0.002	-0.09	-949.	-0.0973
9.17	2.256	0.028	-0.294	0.664	0.001	0.03	-949.	-0.0973
10.16	2.218	0.030	-0.329	0.730	0.001	0.04	-949.	-0.0973
11.18	2.166	0.033	-0.367	0.795	0.004	0.12	-949.	-0.0973
12.19	2.112	0.033	-0.406	0.857	0.006	0.17	-949.	-0.0973
13.20	2.048	0.033	-0.450	0.921	0.005	0.14	-955.	-0.0979
14.21	1.979	0.037	-0.497	0.984	0.007	0.20	-955.	-0.0979
15.21	1.906	0.039	-0.546	1.041	0.008	0.21	-955.	-0.0979

(b) p ≈ -151 rev/s

TABLE 2(CONTD.).

a^o	C.P.$_Z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-3.95	2.815	-0.012	0.096	-0.271	0.016	-1.35	-1571.	-0.1611
-2.94	2.974	-0.012	0.068	-0.201	0.012	-0.94	-1571.	-0.1611
-1.94	3.218	-0.006	0.040	-0.128	0.012	-2.23	-1571.	-0.1611
-0.93	4.158	-0.001	0.013	-0.055	0.013	-20.02	-1565.	-0.1604
0.08	1.261	0.001	-0.015	0.018	0.010	12.65	-1571.	-0.1611
1.08	2.179	0.004	-0.042	0.093	0.008	2.18	-1565.	-0.1604
2.09	2.364	0.009	-0.070	0.167	0.007	0.85	-1565.	-0.1604
3.11	2.432	0.013	-0.099	0.240	0.005	0.39	-1565.	-0.1604
4.11	2.432	0.015	-0.128	0.311	0.002	0.12	-1565.	-0.1604
5.12	2.395	0.020	-0.160	0.383	-0.001	-0.05	-1565.	-0.1604
6.14	2.352	0.028	-0.193	0.454	0.001	0.04	-1565.	-0.1604
7.15	2.309	0.030	-0.226	0.522	-0.002	-0.07	-1565.	-0.1604
8.16	2.258	0.033	-0.263	0.594	-0.006	-0.18	-1565.	-0.1604
9.16	2.217	0.046	-0.297	0.659	-0.001	-0.02	-1565.	-0.1604
10.16	2.161	0.045	-0.337	0.728	-0.006	-0.14	-1565.	-0.1604
11.19	2.116	0.055	-0.374	0.792	-0.001	-0.01	-1565.	-0.1604
12.19	2.068	0.056	-0.413	0.855	-0.001	-0.01	-1558.	-0.1598
13.20	1.997	0.059	-0.460	0.919	0.001	0.02	-1565.	-0.1604
14.22	1.929	0.060	-0.506	0.977	0.000	0.01	-1565.	-0.1604
15.20	1.867	0.064	-0.555	1.036	0.003	0.05	-1565.	-0.1604

(c) $p \approx -249$ rev/s

TABLE 3.   AERODYNAMIC COEFFICIENTS, M = 0.80

a^o	C.P.$_Z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-3.96	2.683	0.002	0.104	-0.278	-0.001	-0.27	0.-0.0000	
-2.96	2.722	0.002	0.075	-0.204	0.000	0.09	0.-0.0000	
-1.94	2.760	0.002	0.045	-0.125	0.001	0.68	0.-0.0000	
-0.94	2.714	0.001	0.019	-0.051	0.002	1.44	0.-0.0000	
0.06	3.414	0.000	-0.007	0.023	0.002	6.91	0.-0.0000	
1.08	2.810	0.000	-0.036	0.100	0.003	11.20	0.-0.0000	
2.08	2.788	-0.000	-0.063	0.177	0.003	-177.66	0.-0.0000	
3.11	2.720	-0.000	-0.092	0.250	0.004	-10.21	0.-0.0000	
4.10	2.682	-0.001	-0.120	0.323	0.004	-5.91	0.-0.0000	
5.11	2.618	-0.001	-0.152	0.398	0.004	-4.39	0.-0.0000	
6.13	2.564	-0.001	-0.183	0.470	0.004	-5.06	0.-0.0000	
7.13	2.510	-0.001	-0.215	0.540	0.004	-4.80	0.-0.0000	
8.15	2.463	-0.001	-0.249	0.614	0.004	-3.66	0.-0.0000	
9.17	2.402	-0.001	-0.285	0.684	0.005	-3.82	0.-0.0000	
10.16	2.334	-0.002	-0.320	0.747	0.005	-2.75	0.-0.0000	
11.18	2.268	-0.001	-0.360	0.816	0.005	-4.46	0.-0.0000	
12.18	2.196	-0.002	-0.400	0.878	0.004	-2.84	0.-0.0000	
13.20	2.121	-0.003	-0.445	0.944	0.004	-1.39	0.-0.0000	
14.21	2.047	-0.000	-0.492	1.006	0.003	-10.29	0.-0.0000	
15.22	1.961	-0.002	-0.543	1.066	0.004	-1.56	0.-0.0000	

(a) p = o

a^o	C.P.$_Z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-3.95	2.767	-0.006	0.101	-0.279	0.012	-1.84	-999.-0.0970	
-2.95	2.845	-0.004	0.072	-0.205	0.012	-3.41	-930.-0.0903	
-1.94	2.875	-0.003	0.045	-0.131	0.011	-3.78	-930.-0.0903	
-0.94	3.255	0.002	0.017	-0.055	0.013	6.14	-930.-0.0903	
0.07	1.924	0.003	-0.012	0.023	0.011	4.23	-930.-0.0903	
1.10	2.486	0.003	-0.040	0.099	0.009	2.75	-930.-0.0903	
2.10	2.586	0.005	-0.068	0.175	0.008	1.52	-930.-0.0903	
3.12	2.578	0.005	-0.097	0.251	0.004	0.91	-930.-0.0903	
4.11	2.539	0.010	-0.126	0.319	0.006	0.63	-930.-0.0903	
5.12	2.485	0.016	-0.158	0.393	0.008	0.48	-930.-0.0903	
6.14	2.437	0.015	-0.191	0.466	0.004	0.27	-924.-0.0897	
7.14	2.410	0.023	-0.223	0.537	0.005	0.21	-924.-0.0897	
8.16	2.359	0.023	-0.257	0.607	0.001	0.03	-924.-0.0897	
9.16	2.305	0.026	-0.295	0.679	-0.000	-0.01	-930.-0.0903	
10.16	2.261	0.029	-0.331	0.748	0.001	0.02	-924.-0.0897	
11.18	2.206	0.031	-0.369	0.815	0.004	0.12	-930.-0.0903	
12.19	2.153	0.032	-0.409	0.880	0.006	0.20	-936.-0.0909	
13.22	2.088	0.032	-0.453	0.947	0.008	0.25	-930.-0.0902	
14.21	2.013	0.032	-0.500	1.007	0.007	0.24	-936.-0.0909	
15.21	1.933	0.034	-0.554	1.070	0.009	0.26	-942.-0.0914	

(b) p ≈ -148 rev/s

TABLE 3(CONTD.).

a^o	$C.P._Z$	C_Y	C_Z	C_m	C_n	$C.P._y$	$p(rad/s)$	p'
-3.95	2.957	-0.009	0.095	-0.281	0.018	-1.93	-1508.	-0.1462
-2.95	3.068	-0.010	0.068	-0.208	0.014	-1.42	-1508.	-0.1460
-1.95	3.277	-0.006	0.041	-0.134	0.014	-2.45	-1502.	-0.1454
-0.93	4.398	-0.004	0.013	-0.058	0.012	-3.11	-1502.	-0.1456
0.06	1.302	-0.000	-0.014	0.018	0.010	-23.85	-1502.	-0.1456
1.08	2.294	0.005	-0.042	0.096	0.010	2.18	-1508.	-0.1460
2.11	2.435	0.005	-0.072	0.176	0.006	1.16	-1502.	-0.1456
3.11	2.533	0.009	-0.098	0.249	0.004	0.46	-1502.	-0.1456
4.10	2.504	0.017	-0.128	0.321	0.005	0.30	-1502.	-0.1456
5.12	2.488	0.021	-0.159	0.395	0.002	0.11	-1502.	-0.1454
6.15	2.433	0.023	-0.192	0.467	-0.002	-0.07	-1502.	-0.1454
7.13	2.376	0.030	-0.226	0.537	0.000	0.00	-1508.	-0.1462
8.16	2.320	0.036	-0.262	0.608	-0.002	-0.05	-1502.	-0.1454
9.16	2.272	0.038	-0.298	0.676	-0.004	-0.10	-1502.	-0.1454
10.17	2.219	0.044	-0.337	0.747	-0.003	-0.06	-1514.	-0.1466
11.19	2.167	0.048	-0.376	0.814	-0.000	-0.00	-1508.	-0.1460
12.18	2.120	0.051	-0.413	0.876	0.002	0.03	-1514.	-0.1466
13.22	2.043	0.052	-0.461	0.942	0.002	0.03	-1508.	-0.1460
14.21	1.975	0.053	-0.509	1.006	0.002	0.03	-1514.	-0.1466
15.21	1.897	0.056	-0.561	1.065	0.004	0.07	-1508.	-0.1460

(c) $p \approx -240$ rev/s

a^o	$C.P._Z$	C_Y	C_Z	C_m	C_n	$C.P._y$	$p(rad/s)$	p'
-3.95	3.058	-0.018	0.094	-0.286	0.018	-1.00	-1967.	-0.1904
-2.96	3.249	-0.013	0.065	-0.212	0.016	-1.17	-1960.	-0.1898
-1.94	3.711	-0.007	0.037	-0.137	0.015	-2.11	-1960.	-0.1898
-0.94	6.293	-0.004	0.010	-0.061	0.011	-2.64	-1960.	-0.1898
0.07	0.918	-0.002	-0.017	0.016	0.008	-4.08	-1960.	-0.1898
1.08	2.086	0.010	-0.045	0.093	0.011	1.15	-1960.	-0.1898
2.11	2.316	0.009	-0.073	0.169	0.005	0.57	-1960.	-0.1898
3.11	2.394	0.017	-0.102	0.243	0.005	0.33	-1960.	-0.1898
4.10	2.438	0.020	-0.130	0.317	0.002	0.09	-1954.	-0.1892
5.12	2.426	0.028	-0.162	0.394	0.000	0.02	-1954.	-0.1889
6.15	2.396	0.033	-0.195	0.468	-0.002	-0.07	-1954.	-0.1889
7.14	2.344	0.037	-0.228	0.535	-0.006	-0.15	-1954.	-0.1889
8.16	2.283	0.044	-0.266	0.606	-0.006	-0.13	-1954.	-0.1892
9.16	2.212	0.051	-0.305	0.675	-0.007	-0.14	-1954.	-0.1892
10.17	2.154	0.055	-0.345	0.744	-0.009	-0.17	-1960.	-0.1898
11.19	2.105	0.061	-0.386	0.812	-0.007	-0.11	-1960.	-0.1898
12.19	2.052	0.068	-0.428	0.879	-0.003	-0.05	-1954.	-0.1889
13.20	1.997	0.071	-0.470	0.938	0.000	0.00	-1960.	-0.1895
14.22	1.925	0.072	-0.519	1.000	-0.000	-0.00	-1960.	-0.1895
15.21	1.859	0.075	-0.571	1.061	0.003	0.04	-1967.	-0.1904

(d) $p \approx -312$ rev/s

TABLE 4. AERODYNAMIC COEFFICIENTS, M = 0.85

a^o	C.P.$_Z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-3.98	2.771	0.003	0.103	-0.286	-0.001	-0.45	0.-0.0000	
-2.97	2.832	0.003	0.074	-0.211	-0.001	-0.30	0.-0.0000	
-1.95	2.887	0.002	0.046	-0.134	0.000	0.11	0.-0.0000	
-0.92	2.911	0.001	0.018	-0.054	0.001	0.48	0.-0.0000	
0.07	3.049	0.001	-0.008	0.025	0.001	1.39	0.-0.0000	
1.07	2.984	0.001	-0.034	0.102	0.002	2.32	0.-0.0000	
2.11	2.860	0.000	-0.062	0.180	0.002	4.51	0.-0.0000	
3.12	2.838	0.000	-0.091	0.257	0.002	26.21	0.-0.0000	
4.10	2.781	-0.000	-0.119	0.332	0.003	-9.56	0.-0.0000	
5.11	2.721	-0.001	-0.149	0.406	0.003	-5.25	0.-0.0000	
6.13	2.651	-0.001	-0.181	0.480	0.003	-5.75	0.-0.0000	
7.14	2.607	-0.001	-0.212	0.553	0.004	-4.60	0.-0.0000	
8.16	2.552	-0.001	-0.246	0.628	0.004	-3.26	0.-0.0000	
9.16	2.488	-0.001	-0.282	0.701	0.004	-3.43	0.-0.0000	
10.16	2.415	-0.002	-0.320	0.773	0.004	-2.57	0.-0.0000	
11.19	2.336	-0.001	-0.361	0.844	0.004	-4.85	0.-0.0000	
12.19	2.261	-0.001	-0.404	0.913	0.005	-4.52	0.-0.0000	
13.20	2.172	-0.002	-0.445	0.966	0.004	-1.81	0.-0.0000	
14.22	2.086	-0.001	-0.493	1.028	0.002	-3.87	0.-0.0000	
15.23	1.906	-0.003	-0.548	1.094	0.002	-0.70	0.-0.0000	

(a) p = o

a^o	C.P.$_Z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-3.96	2.911	-0.010	0.099	-0.287	0.008	-0.84	-942.	-0.0868
-2.95	3.002	-0.004	0.071	-0.213	0.012	-2.63	-949.	-0.0873
-1.94	3.101	-0.004	0.044	-0.137	0.009	-2.16	-949.	-0.0873
-0.94	3.479	0.000	0.017	-0.059	0.010	27.47	-949.	-0.0873
0.07	1.901	0.002	-0.011	0.020	0.009	5.63	-949.	-0.0873
1.09	2.613	0.004	-0.039	0.101	0.009	2.08	-949.	-0.0873
2.09	2.695	0.006	-0.066	0.177	0.008	1.21	-949.	-0.0873
3.11	2.699	0.006	-0.095	0.256	0.004	0.65	-942.	-0.0868
4.10	2.633	0.010	-0.125	0.330	0.003	0.32	-942.	-0.0868
5.13	2.615	0.014	-0.156	0.409	0.003	0.20	-942.	-0.0868
6.14	2.574	0.015	-0.189	0.486	0.001	0.04	-942.	-0.0868
7.15	2.503	0.022	-0.220	0.551	0.001	0.02	-949.	-0.0873
8.16	2.451	0.024	-0.255	0.625	-0.003	-0.11	-949.	-0.0873
9.16	2.401	0.025	-0.291	0.700	-0.004	-0.18	-942.	-0.0868
10.18	2.347	0.029	-0.328	0.770	-0.002	-0.06	-949.	-0.0873
11.20	2.279	0.031	-0.369	0.841	0.002	0.05	-949.	-0.0872
12.20	2.211	0.031	-0.410	0.906	0.005	0.17	-949.	-0.0873
13.23	2.140	0.027	-0.456	0.975	0.006	0.20	-955.	-0.0879
14.22	2.066	0.033	-0.503	1.039	0.008	0.26	-955.	-0.0878
15.22	1.975	0.032	-0.556	1.099	0.006	0.19	-955.	-0.0879

(b) p ≈ -151 rev/s

TABLE 4(CONTD.).

a^o	C.P.$_Z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-3.97	3.060	-0.010	0.096	-0.293	0.017	-1.63	-1495.	-0.1375
-2.96	3.219	-0.006	0.068	-0.218	0.017	-2.68	-1489.	-0.1369
-1.94	3.442	-0.007	0.040	-0.139	0.013	-1.94	-1489.	-0.1369
-0.94	4.246	-0.003	0.014	-0.060	0.011	-3.51	-1489.	-0.1369
0.06	1.368	0.001	-0.013	0.017	0.011	9.93	-1483.	-0.1363
1.08	2.346	0.004	-0.042	0.098	0.008	2.13	-1483.	-0.1363
2.10	2.584	0.007	-0.068	0.177	0.006	0.82	-1483.	-0.1363
3.11	2.638	0.012	-0.095	0.251	0.005	0.41	-1477.	-0.1357
4.11	2.645	0.017	-0.124	0.329	0.003	0.19	-1477.	-0.1357
5.12	2.591	0.020	-0.157	0.406	-0.001	-0.04	-1477.	-0.1357
6.14	2.532	0.027	-0.190	0.482	-0.001	-0.04	-1477.	-0.1357
7.15	2.497	0.032	-0.223	0.556	-0.003	-0.09	-1477.	-0.1357
8.18	2.407	0.035	-0.260	0.627	-0.006	-0.17	-1477.	-0.1357
9.17	2.362	0.040	-0.295	0.698	-0.006	-0.16	-1477.	-0.1357
10.17	2.305	0.044	-0.333	0.768	-0.006	-0.13	-1477.	-0.1357
11.19	2.246	0.046	-0.374	0.840	-0.003	-0.06	-1477.	-0.1357
12.19	2.187	0.050	-0.414	0.905	0.001	0.02	-1477.	-0.1357
13.22	2.115	0.050	-0.459	0.971	0.002	0.03	-1477.	-0.1357
14.22	2.032	0.054	-0.507	1.031	0.003	0.06	-1477.	-0.1357
15.22	1.951	0.055	-0.561	1.095	0.003	0.06	-1483.	-0.1363

(c) p $\approx$ -236 rev/s

a^o	C.P.$_Z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-3.96	3.210	-0.019	0.091	-0.294	0.018	-0.93	-1948.	-0.1790
-2.96	3.396	-0.015	0.065	-0.220	0.016	-1.03	-1948.	-0.1790
-1.94	3.858	-0.010	0.037	-0.141	0.013	-1.29	-1948.	-0.1790
-0.93	6.161	-0.003	0.010	-0.062	0.013	-4.05	-1954.	-0.1796
0.06	0.844	0.000	-0.016	0.014	0.011	27.51	-1948.	-0.1790
1.08	2.203	0.005	-0.043	0.094	0.008	1.52	-1948.	-0.1790
2.10	2.472	0.012	-0.070	0.174	0.007	0.56	-1948.	-0.1790
3.12	2.517	0.016	-0.098	0.247	0.005	0.32	-1948.	-0.1790
4.10	2.522	0.022	-0.128	0.322	0.003	0.12	-1948.	-0.1790
5.11	2.522	0.026	-0.159	0.400	-0.001	-0.04	-1948.	-0.1790
6.14	2.484	0.034	-0.191	0.475	-0.003	-0.07	-1948.	-0.1790
7.15	2.413	0.037	-0.223	0.539	-0.006	-0.15	-1954.	-0.1796
8.15	2.355	0.045	-0.260	0.611	-0.007	-0.15	-1954.	-0.1796
9.17	2.280	0.050	-0.299	0.683	-0.010	-0.20	-1954.	-0.1796
10.18	2.223	0.057	-0.339	0.753	-0.009	-0.16	-1960.	-0.1802
11.20	2.164	0.062	-0.380	0.823	-0.007	-0.12	-1954.	-0.1796
12.20	2.111	0.062	-0.420	0.886	-0.005	-0.08	-1960.	-0.1802
13.21	2.057	0.065	-0.463	0.953	-0.001	-0.02	-1960.	-0.1802
14.22	1.978	0.067	-0.512	1.012	0.001	0.01	-1960.	-0.1802
15.22	1.909	0.071	-0.564	1.076	0.003	0.04	-1967.	-0.1808

(d) p $\approx$ -311 rev/s

TABLE 5. AERODYNAMIC COEFFICIENTS, M = 0.90

a°	$C.P._Z$	C_Y	C_Z	C_m	C_n	$C.P._y$	p(rad/s)	p'
-3.98	3.139	0.003	0.096	-0.303	-0.002	-0.65	0.-0.0000	
-2.97	3.250	0.002	0.069	-0.225	-0.001	-0.57	0.-0.0000	
-1.96	3.367	0.002	0.043	-0.144	-0.001	-0.56	0.-0.0000	
-0.92	3.366	0.001	0.017	-0.057	0.000	0.01	0.-0.0000	
0.07	3.282	0.001	-0.007	0.025	0.000	0.61	0.-0.0000	
1.08	3.329	0.000	-0.032	0.107	0.001	2.64	0.-0.0000	
2.09	3.241	0.000	-0.058	0.189	0.001	6.62	0.-0.0000·	
3.10	3.190	0.000	-0.085	0.270	0.002	67.69	0.-0.0000	
4.10	3.045	-0.000	-0.114	0.346	0.003	-5.96	0.-0.0000	
5.12	2.982	-0.001	-0.143	0.426	0.003	-2.47	0.-0.0000	
6.14	2.928	-0.002	-0.173	0.506	0.003	-2.05	0.-0.0000	
7.14	2.874	-0.002	-0.204	0.587	0.004	-1.87	0.-0.0000	
8.17	2.772	-0.002	-0.238	0.660	0.005	-1.83	0.-0.0000	
9.17	2.693	-0.002	-0.274	0.738	0.005	-1.83	0.-0.0000	
10.17	2.614	-0.002	-0.311	0.814	0.004	-1.97	0.-0.0000	
11.20	2.502	-0.000	-0.352	0.882	0.004	-19.83	0.-0.0000	
12.19	2.400	-0.001	-0.396	0.950	0.003	-3.64	0.-0.0000	
13.21	2.297	-0.000	-0.444	1.019	0.002	-4.68	0.-0.0000	
14.23	2.202	0.001	-0.494	1.087	-0.000	-0.28	0.-0.0000	
15.22	2.105	0.000	-0.551	1.160	-0.001	-1.72	0.-0.0000	

(a) p = o

a°	$C.P._Z$	C_Y	C_Z	C_m	C_n	$C.P._y$	p(rad/s)	p'
-3.96	3.237	-0.009	0.094	-0.306	0.011	-1.18	-949.-0.0831	
-2.97	3.266	-0.007	0.068	-0.222	0.010	-1.42	-949.-0.0831	
-1.96	3.281	-0.004	0.043	-0.142	0.008	-1.90	-942.-0.0826	
-0.94	3.631	-0.002	0.016	-0.060	0.008	-3.53	-942.-0.0826	
0.06	2.426	-0.000	-0.008	0.020	0.006	-512.87	-949.-0.0831	
1.07	3.037	0.003	-0.034	0.105	0.005	1.94	-942.-0.0826	
2.08	2.977	0.005	-0.061	0.183	0.004	0.87	-949.-0.0831	
3.10	2.984	0.007	-0.088	0.263	0.003	0.34	-942.-0.0826	
4.10	2.976	0.011	-0.115	0.342	0.001	0.08	-942.-0.0826	
5.13	2.913	0.014	-0.145	0.423	-0.001	-0.10	-942.-0.0826	
6.13	2.811	0.017	-0.176	0.496	-0.003	-0.18	-949.-0.0831	
7.14	2.759	0.021	-0.208	0.575	-0.005	-0.23	-942.-0.0826	
8.15	2.680	0.025	-0.243	0.653	-0.006	-0.26	-942.-0.0826	
9.19	2.585	0.028	-0.281	0.726	-0.006	-0.22	-949.-0.0831	
10.17	2.519	0.030	-0.317	0.797	-0.005	-0.17	-955.-0.0837	
11.20	2.432	0.030	-0.357	0.869	-0.002	-0.07	-955.-0.0837	
12.20	2.338	0.030	-0.401	0.936	0.001	0.04	-955.-0.0837	
13.22	2.249	0.029	-0.447	1.005	0.004	0.14	-961.-0.0842	
14.22	2.153	0.031	-0.496	1.067	0.004	0.12	-961.-0.0842	
15.22	2.051	0.033	-0.551	1.129	0.003	0.10	-961.-0.0842	

(b) p ≈ -151 rev/s

TABLE 5(CONTD.).

a^o	C.P.$_Z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-3.96	3.344	-0.015	0.092	-0.306	0.016	-1.03	-1489.	-0.1305
-2.96	3.422	-0.011	0.065	-0.223	0.013	-1.21	-1489.	-0.1303
-1.94	3.705	-0.007	0.039	-0.144	0.011	-1.55	-1489.	-0.1305
-0.94	4.271	-0.003	0.014	-0.061	0.000	-2.89	-1483.	-0.1299
0.06	1.700	0.000	-0.012	0.020	0.007	25.05	-1483.	-0.1299
1.08	2.752	0.004	-0.037	0.101	0.005	1.15	-1483.	-0.1299
2.08	2.870	0.008	-0.063	0.181	0.003	0.38	-1489.	-0.1305
3.11	2.928	0.013	-0.089	0.262	0.000	0.04	-1483.	-0.1299
4.11	2.871	0.017	-0.118	0.340	-0.002	-0.10	-1483.	-0.1299
5.11	2.833	0.022	-0.147	0.417	-0.005	-0.21	-1489.	-0.1305
6.13	2.787	0.028	-0.178	0.496	-0.008	-0.30	-1489.	-0.1305
7.14	2.726	0.033	-0.211	0.574	-0.011	-0.34	-1489.	-0.1305
8.15	2.640	0.039	-0.247	0.653	-0.014	-0.36	-1489.	-0.1305
9.16	2.572	0.045	-0.284	0.731	-0.015	-0.33	-1489.	-0.1305
10.17	2.467	0.046	-0.321	0.793	-0.011	-0.25	-1489.	-0.1305
11.19	2.394	0.046	-0.360	0.862	-0.007	-0.15	-1495.	-0.1310
12.19	2.326	0.047	-0.401	0.933	-0.004	-0.08	-1495.	-0.1308
13.21	2.234	0.050	-0.447	1.000	-0.004	-0.07	-1502.	-0.1316
14.23	2.130	0.053	-0.500	1.065	-0.004	-0.07	-1502.	-0.1316
15.22	2.028	0.055	-0.553	1.122	-0.003	-0.05	-1508.	-0.1321

(c) $p \approx -237$ rev/s

a^o	C.P.$_Z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-3.95	3.478	-0.020	0.088	-0.308	0.020	-0.96	-1942.	-0.1698
-2.96	3.685	-0.015	0.062	-0.229	0.017	-1.12	-1935.	-0.1693
-1.94	4.030	-0.009	0.036	-0.145	0.013	-1.41	-1942.	-0.1698
-0.94	6.219	-0.005	0.010	-0.065	0.011	-2.35	-1935.	-0.1693
0.07	1.131	0.001	-0.013	0.015	0.008	13.13	-1935.	-0.1693
1.10	2.512	0.006	-0.040	0.100	0.005	0.77	-1929.	-0.1687
2.09	2.765	0.011	-0.064	0.177	0.002	0.19	-1935.	-0.1693
3.10	2.824	0.017	-0.092	0.259	-0.002	-0.09	-1935.	-0.1693
4.10	2.865	0.023	-0.118	0.339	-0.005	-0.23	-1935.	-0.1693
5.11	2.744	0.028	-0.150	0.412	-0.008	-0.27	-1935.	-0.1693
6.14	2.704	0.035	-0.181	0.491	-0.011	-0.33	-1935.	-0.1693
7.15	2.645	0.043	-0.215	0.569	-0.016	-0.38	-1935.	-0.1693
8.15	2.576	0.049	-0.251	0.646	-0.020	-0.40	-1935.	-0.1693
9.20	2.488	0.056	-0.290	0.722	-0.021	-0.37	-1935.	-0.1693
10.17	2.390	0.060	-0.328	0.784	-0.018	-0.30	-1942.	-0.1698
11.20	2.318	0.062	-0.370	0.857	-0.014	-0.23	-1935.	-0.1693
12.20	2.252	0.062	-0.410	0.925	-0.009	-0.15	-1929.	-0.1687
13.21	2.181	0.063	-0.455	0.992	-0.006	-0.10	-1935.	-0.1693
14.23	2.085	0.066	-0.506	1.054	-0.005	-0.08	-1929.	-0.1687
15.22	1.993	0.069	-0.559	1.114	-0.004	-0.06	-1929.	-0.1687

(d) $p \approx -308$ rev/s

TABLE 6. AERODYNAMIC COEFFICIENTS, M = 0.95

a°	$C.P._Z$	C_Y	C_Z	C_m	C_n	$C.P._y$	$p(rad/s)$	p'
-3.97	4.352	-0.001	0.079	-0.344	-0.000	0.29	0.-	-0.0000
-2.97	4.858	0.001	0.053	-0.259	-0.002	-2.05	0.-	-0.0000
-1.94	4.952	0.001	0.033	-0.163	-0.002	-1.62	0.-	-0.0000
-0.94	5.069	0.001	0.013	-0.067	-0.001	-1.20	0.-	-0.0000
0.07	10.657	0.001	-0.003	0.029	-0.000	-0.67	0.-	-0.0000
1.09	6.145	0.000	-0.021	0.128	0.000	0.48	0.-	-0.0000
2.10	5.280	0.000	-0.042	0.223	0.000	7.76	0.-	-0.0000
3.11	4.613	0.001	-0.067	0.309	-0.00?	-0.39	0.-	-0.0000
4.10	4.240	0.004	-0.093	0.395	-0.003	-0.98	0.-	-0.0000
5.12	3.842	0.003	-0.123	0.473	-0.003	-1.00	0.-	-0.0000
6.15	3.675	0.007	-0.152	0.559	-0.008	-1.21	0.-	-0.0000
7.16	3.471	0.008	-0.184	0.638	-0.011	-1.25	0.-	-0.0000
8.17	3.344	0.010	-0.216	0.723	-0.012	-1.29	0.-	-0.0000
9.17	3.069	0.007	-0.255	0.787	-0.009	-1.31	0.-	-0.0000
10.18	2.960	0.008	-0.292	0.865	-0.010	-1.22	0.-	-0.0000
11.20	2.776	0.010	-0.337	0.935	-0.010	-1.07	0.-	-0.0000
12.20	2.508	0.013	-0.386	1.002	-0.016	-1.19	0.-	-0.0000
13.23	2.496	0.019	-0.448	1.079	-0.024	-1.21	0.-	-0.0000
14.23	2.246	0.014	-0.512	1.150	-0.021	-1.50	0.-	-0.0000
15.25	2.138	0.006	-0.570	1.218	-0.008	-1.34	0.-	-0.0000

(a) p = o

a°	$C.P._Z$	C_Y	C_Z	C_m	C_n	$C.P._y$	$p(rad/s)$	p'
-3.97	4.284	-0.020	0.079	-0.340	0.024	-1.20	-936.	-0.0784
-2.97	4.959	-0.014	0.052	-0.256	0.019	-1.32	-936.	-0.0783
-1.94	5.464	-0.009	0.030	-0.164	0.014	-1.52	-936.	-0.0784
-0.94	5.745	-0.004	0.012	-0.069	0.009	-2.19	-930.	-0.0778
0.07	3.294	-0.000	-0.007	0.024	0.006	-14.13	-930.	-0.0779
1.10	4.626	0.004	-0.026	0.121	0.002	0.54	-936.	-0.0783
2.10	4.281	0.008	-0.048	0.204	-0.001	-0.07	-930.	-0.0778
3.12	4.130	0.014	-0.072	0.295	-0.007	-0.47	-924.	-0.0773
4.11	3.946	0.022	-0.097	0.384	-0.015	-0.66	-930.	-0.0779
5.12	3.622	0.026	-0.127	0.460	-0.018	-0.69	-936.	-0.0784
6.14	3.508	0.037	-0.156	0.549	-0.029	-0.80	-936.	-0.0784
7.16	3.400	0.048	-0.187	0.636	-0.041	-0.86	-936.	-0.0784
8.17	3.275	0.048	-0.218	0.713	-0.039	-0.81	-942.	-0.0790
9.17	3.068	0.044	-0.255	0.789	-0.032	-0.72	-942.	-0.0788
10.18	2.944	0.016	-0.294	0.865	0.006	0.37	-942.	-0.0788
11.20	2.773	0.003	-0.339	0.940	0.024	7.24	-942.	-0.0790
12.21	2.573	0.004	-0.389	1.002	0.025	6.17	-942.	-0.0788
13.23	2.402	-0.003	-0.444	1.067	0.036	-12.65	-942.	-0.0788
14.25	2.260	-0.015	-0.503	1.137	0.052	-3.43	-949.	-0.0794
15.25	2.136	-0.018	-0.562	1.200	0.058	-3.25	-949.	-0.0794

(b) p ≈ -149 rev/s

TABLE 6(CONTD.).

a^o	C.P.$_Z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-3.99	4.180	-0.028	0.080	-0.334	0.032	-1.14	-1508.	-0.1261
-2.96	4.613	-0.020	0.054	-0.249	0.025	-1.22	-1508.	-0.1261
-1.94	5.265	-0.013	0.030	-0.159	0.019	-1.41	-1508.	-0.1261
-0.94	6.253	-0.006	0.011	-0.068	0.012	-2.03	-1502.	-0.1256
0.06	2.425	-0.000	-0.009	0.021	0.008	-512.79	-1508.	-0.1261
1.08	4.345	0.008	-0.027	0.118	0.000	0.02	-1508.	-0.1261
2.10	3.769	0.012	-0.053	0.199	-0.002	-0.14	-1502.	-0.1256
3.12	3.712	0.020	-0.078	0.289	-0.009	-0.44	-1495.	-0.1251
4.11	3.645	0.029	-0.103	0.374	-0.017	-0.61	-1502.	-0.1256
5.12	3.372	0.033	-0.133	0.449	-0.020	-0.60	-1502.	-0.1256
6.14	3.279	0.044	-0.163	0.534	-0.031	-0.70	-1495.	-0.1251
7.16	3.203	0.056	-0.194	0.620	-0.042	-0.75	-1502.	-0.1256
8.17	3.150	0.066	-0.227	0.705	-0.051	-0.78	-1495.	-0.1251
9.18	2.956	0.067	-0.264	0.780	-0.048	-0.72	-1502.	-0.1256
10.19	2.856	0.045	-0.301	0.860	-0.016	-0.35	-1502.	-0.1256
11.21	2.738	0.028	-0.344	0.942	0.007	0.23	-1502.	-0.1256
12.21	2.564	0.027	-0.392	1.006	0.012	0.42	-1495.	-0.1251
13.24	2.354	0.028	-0.453	1.067	0.014	0.49	-1495.	-0.1251
14.24	2.225	0.021	-0.509	1.132	0.025	1.17	-1495.	-0.1251
15.24	2.107	0.006	-0.571	1.203	0.047	8.23	-1495.	-0.1251

(c) p ≈ -239 rev/s

a^o	C.P.$_Z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-3.99	4.265	-0.034	0.079	-0.337	0.037	-1.08	-1954.	-0.1635
-2.96	4.791	-0.026	0.053	-0.252	0.030	-1.17	-1954.	-0.1635
-1.94	5.625	-0.017	0.029	-0.163	0.022	-1.32	-1954.	-0.1635
-0.95	8.655	-0.008	0.008	-0.073	0.014	-1.79	-1954.	-0.1635
0.07	1.830	0.001	-0.011	0.020	0.007	8.46	-1954.	-0.1632
1.10	3.480	0.010	-0.032	0.112	-0.000	-0.03	-1954.	-0.1632
2.08	3.784	0.019	-0.053	0.200	-0.009	-0.46	-1948.	-0.1627
3.11	3.576	0.026	-0.080	0.284	-0.014	-0.54	-1954.	-0.1635
4.10	3.423	0.034	-0.107	0.365	-0.021	-0.60	-1948.	-0.1627
5.12	3.312	0.047	-0.136	0.450	-0.033	-0.70	-1948.	-0.1627
6.13	3.209	0.061	-0.167	0.536	-0.047	-0.77	-1954.	-0.1632
7.15	3.034	0.064	-0.201	0.608	-0.045	-0.71	-1948.	-0.1627
8.17	2.935	0.075	-0.236	0.694	-0.054	-0.73	-1954.	-0.1632
9.18	2.824	0.080	-0.273	0.772	-0.055	-0.70	-1954.	-0.1632
10.20	2.709	0.073	-0.315	0.852	-0.041	-0.56	-1954.	-0.1632
11.23	2.610	0.053	-0.355	0.926	-0.012	-0.22	-1948.	-0.1627
12.21	2.466	0.039	-0.400	0.996	0.009	0.24	-1954.	-0.1632
13.24	2.346	0.034	-0.451	1.059	0.020	0.61	-1954.	-0.1632
14.24	2.207	0.031	-0.510	1.127	0.027	0.86	-1954.	-0.1632
15.24	2.096	0.027	-0.572	1.200	0.036	1.35	-1954.	-0.1632

(d) p ≈ -311 rev/s

TABLE 7. AERODYNAMIC COEFFICIENTS, M = 1.4

a^o	$C.P._Z$	C_Y	C_Z	C_m	C_n	$C.P._y$	p(rad/s)	p'
-3.96	1.624	0.002	0.166	-0.270	-0.006	-2.68	0.-0.0000	
-2.95	1.667	0.002	0.119	-0.198	-0.005	-2.46	0.-0.0000	
-1.94	1.673	0.002	0.075	-0.125	-0.005	-2.35	0.-0.0000	
-0.94	1.718	0.002	0.031	-0.053	-0.004	-2.44	0.-0.0000	
0.08	1.495	0.002	-0.014	0.020	-0.004	-2.38	0.-0.0000	
1.09	1.623	0.001	-0.057	0.092	-0.003	-2.34	0.-0.0000	
2.12	1.620	0.001	-0.103	0.166	-0.003	-2.47	0.-0.0000	
3.13	1.621	0.001	-0.146	0.237	-0.002	-2.60	0.-0.0000	
4.13	1.601	0.001	-0.193	0.309	-0.002	-2.21	0.-0.0000	
5.15	1.583	0.002	-0.241	0.381	-0.002	-1.00	0.-0.0000	
6.16	1.552	0.001	-0.291	0.452	-0.002	-1.70	0.-0.0000	
7.20	1.521	0.001	-0.345	0.525	-0.001	-1.40	0.-0.0000	
8.22	1.475	0.001	-0.401	0.596	-0.001	-1.32	0.-0.0000	
9.22	1.445	0.001	-0.461	0.665	-0.002	-1.88	0.-0.0000	
10.23	1.402	-0.000	-0.525	0.735	-0.002	6.13	0.-0.0000	
11.28	1.355	-0.001	-0.594	0.805	-0.003	4.59	0.-0.0000	
12.27	1.306	-0.001	-0.666	0.870	-0.002	2.66	0.-0.0000	
13.30	1.253	-0.001	-0.748	0.937	-0.002	2.23	0.-0.0000	
14.30	1.198	-0.004	-0.834	1.000	-0.002	0.42	0.-0.0000	
15.32	1.137	-0.003	-0.933	1.061	-0.002	0.67	0.-0.0000	

(a) p = o

a^o	$C.P._Z$	C_Y	C_Z	C_m	C_n	$C.P._y$	p(rad/s)	p'
-4.00	1.670	-0.003	0.163	-0.273	0.000	-0.16	-942.-0.0586	
-2.98	1.699	-0.001	0.118	-0.201	0.000	-0.10	-936.-0.0582	
-1.96	1.747	-0.000	0.073	-0.128	0.000	-0.04	-936.-0.0582	
-0.95	1.785	0.001	0.030	-0.054	0.000	0.32	-936.-0.0582	
0.06	1.661	0.002	-0.012	0.020	0.000	0.06	-942.-0.0586	
1.07	1.664	0.002	-0.056	0.094	-0.000	-0.02	-936.-0.0582	
2.11	1.681	0.004	-0.100	0.169	-0.000	-0.07	-942.-0.0586	
3.11	1.663	0.005	-0.145	0.240	-0.000	-0.10	-942.-0.0586	
4.12	1.625	0.006	-0.192	0.311	-0.001	-0.10	-936.-0.0582	
5.14	1.591	0.008	-0.241	0.383	-0.001	-0.14	-936.-0.0582	
6.19	1.563	0.010	-0.292	0.457	-0.001	-0.15	-942.-0.0586	
7.19	1.525	0.012	-0.345	0.527	-0.002	-0.17	-949.-0.0589	
8.21	1.488	0.014	-0.401	0.598	-0.002	-0.17	-955.-0.0593	
9.21	1.441	0.016	-0.463	0.668	-0.003	-0.16	-955.-0.0593	
10.23	1.394	0.019	-0.529	0.737	-0.003	-0.17	-961.-0.0597	
11.26	1.349	0.021	-0.597	0.805	-0.004	-0.21	-955.-0.0593	
12.26	1.304	0.022	-0.668	0.871	-0.005	-0.24	-955.-0.0592	
13.29	1.254	0.022	-0.748	0.938	-0.005	-0.23	-955.-0.0593	
14.30	1.100	0.022	-0.835	1.001	-0.003	-0.15	-961.-0.0597	
15.31	1.143	0.020	-0.931	1.064	0.003	0.13	-961.-0.0597	

(b) p ≈ -151 rev/s

TABLE 7(CONTD.).

a^o	C.P.$_z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-4.00	1.744	-0.006	0.159	-0.277	0.004	-0.61	-1508.	-0.0935
-2.98	1.785	-0.005	0.115	-0.205	0.003	-0.74	-1508.	-0.0935
-1.96	1.876	-0.003	0.071	-0.131	0.003	-1.12	-1508.	-0.0935
-0.95	2.039	-0.001	0.027	-0.056	0.002	-3.02	-1508.	-0.0935
0.07	1.407	0.001	-0.013	0.019	0.002	1.72	-1508.	-0.0935
1.10	1.644	0.003	-0.058	0.095	0.001	0.52	-1508.	-0.0935
2.11	1.677	0.005	-0.100	0.168	0.001	0.18	-1514.	-0.0939
3.12	1.360	0.001	-0.166	0.226	0.012	13.77	-1508.	-0.0935
4.11	1.540	0.009	-0.190	0.312	-0.001	-0.11	-1508.	-0.0935
5.14	1.612	0.011	-0.239	0.385	-0.002	-0.16	-1508.	-0.0935
6.16	1.571	0.014	-0.290	0.456	-0.003	-0.21	-1514.	-0.0939
7.19	1.536	0.016	-0.344	0.528	-0.004	-0.24	-1514.	-0.0939
8.20	1.498	0.019	-0.399	0.598	-0.005	-0.25	-1514.	-0.0939
9.21	1.443	0.023	-0.462	0.667	-0.006	-0.24	-1521.	-0.0943
10.23	1.395	0.027	-0.528	0.736	-0.007	-0.25	-1521.	-0.0943
11.26	1.348	0.030	-0.597	0.805	-0.007	-0.25	-1527.	-0.0947
12.26	1.301	0.033	-0.669	0.870	-0.008	-0.24	-1527.	-0.0947
13.29	1.254	0.032	-0.749	0.939	-0.005	-0.17	-1527.	-0.0947
14.31	1.204	0.028	-0.835	1.005	0.002	0.06	-1527.	-0.0947
15.31	1.156	0.016	-0.927	1.071	0.019	1.16	-1527.	-0.0947

(c) p $\approx$ -241 rev/s

a^o	C.P.$_z$	C_Y	C_Z	C_m	C_n	C.P.$_y$	p(rad/s)	p'
-3.99	1.780	-0.010	0.158	-0.282	0.007	-0.70	-1923.	-0.1191
-2.98	1.884	-0.007	0.111	-0.209	0.006	-0.77	-1923.	-0.1191
-1.96	1.961	-0.005	0.068	-0.134	0.004	-0.91	-1923.	-0.1191
-0.95	2.353	-0.002	0.025	-0.059	0.003	-1.55	-1923.	-0.1191
0.07	1.244	0.001	-0.014	0.018	0.002	2.46	-1923.	-0.1191
1.08	1.605	0.003	-0.058	0.092	0.001	0.20	-1916.	-0.1187
2.11	1.667	0.006	-0.101	0.168	-0.000	-0.07	-1916.	-0.1187
3.15	1.572	0.009	-0.146	0.244	-0.002	-0.21	-1916.	-0.1187
4.12	1.658	0.011	-0.189	0.313	-0.003	-0.22	-1923.	-0.1191
5.14	1.626	0.014	-0.237	0.386	-0.004	-0.27	-1916.	-0.1187
6.19	1.585	0.017	-0.289	0.459	-0.005	-0.29	-1923.	-0.1191
7.20	1.537	0.020	-0.344	0.528	-0.006	-0.30	-1923.	-0.1191
8.20	1.492	0.023	-0.401	0.598	-0.007	-0.29	-1916.	-0.1187
9.21	1.446	0.026	-0.461	0.667	-0.007	-0.29	-1916.	-0.1187
10.24	1.395	0.030	-0.528	0.737	-0.007	-0.24	-1923.	-0.1191
11.26	1.348	0.033	-0.598	0.806	-0.006	-0.19	-1923.	-0.1191
12.27	1.301	0.035	-0.671	0.872	-0.004	-0.12	-1916.	-0.1187
13.29	1.257	0.035	-0.749	0.941	-0.001	-0.02	-1916.	-0.1187
14.30	1.216	0.027	-0.831	1.010	0.012	0.42	-1916.	-0.1187
15.33	1.166	0.013	-0.923	1.078	0.032	2.51	-1910.	-0.1183

(d) p $\approx$ -305 rev/s

shield, protecting
rear balance cage

42 mm

roll rate pickup
(magnet and hall
effect sensor)

air bearing

driving air
ducting

air motor

boundary layer trip band,
0.4 mm balls at 1.2 mm spacing

246 mm

52.5 mm
diam
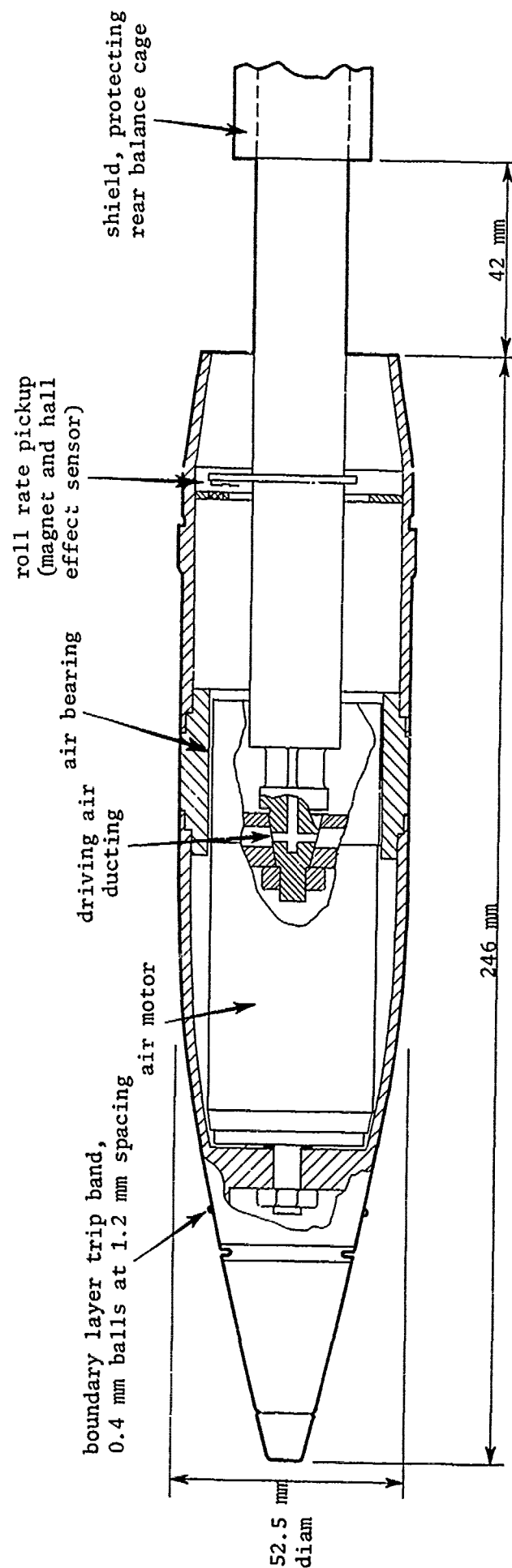
Figure 1. 105mm shell model, showing internal details
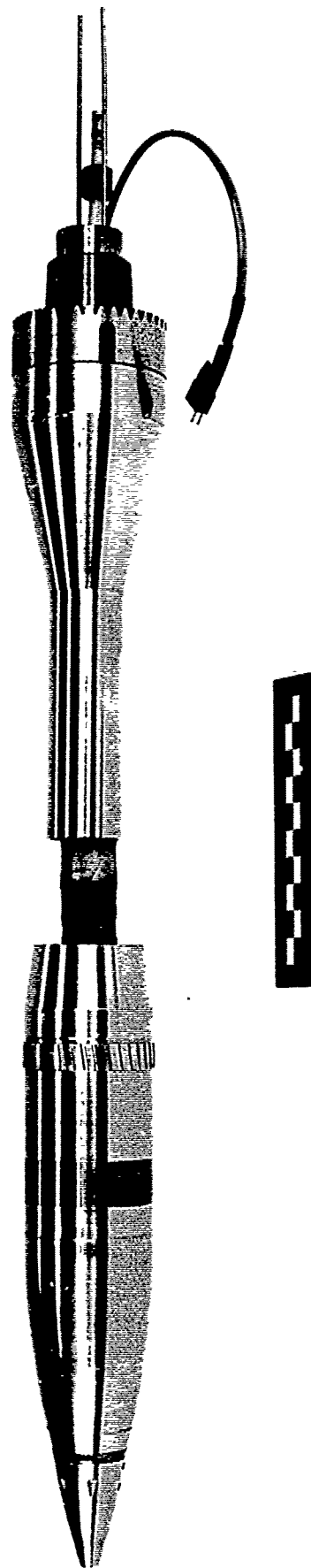
Figure 2.   Assembly of model, balance and balance shield
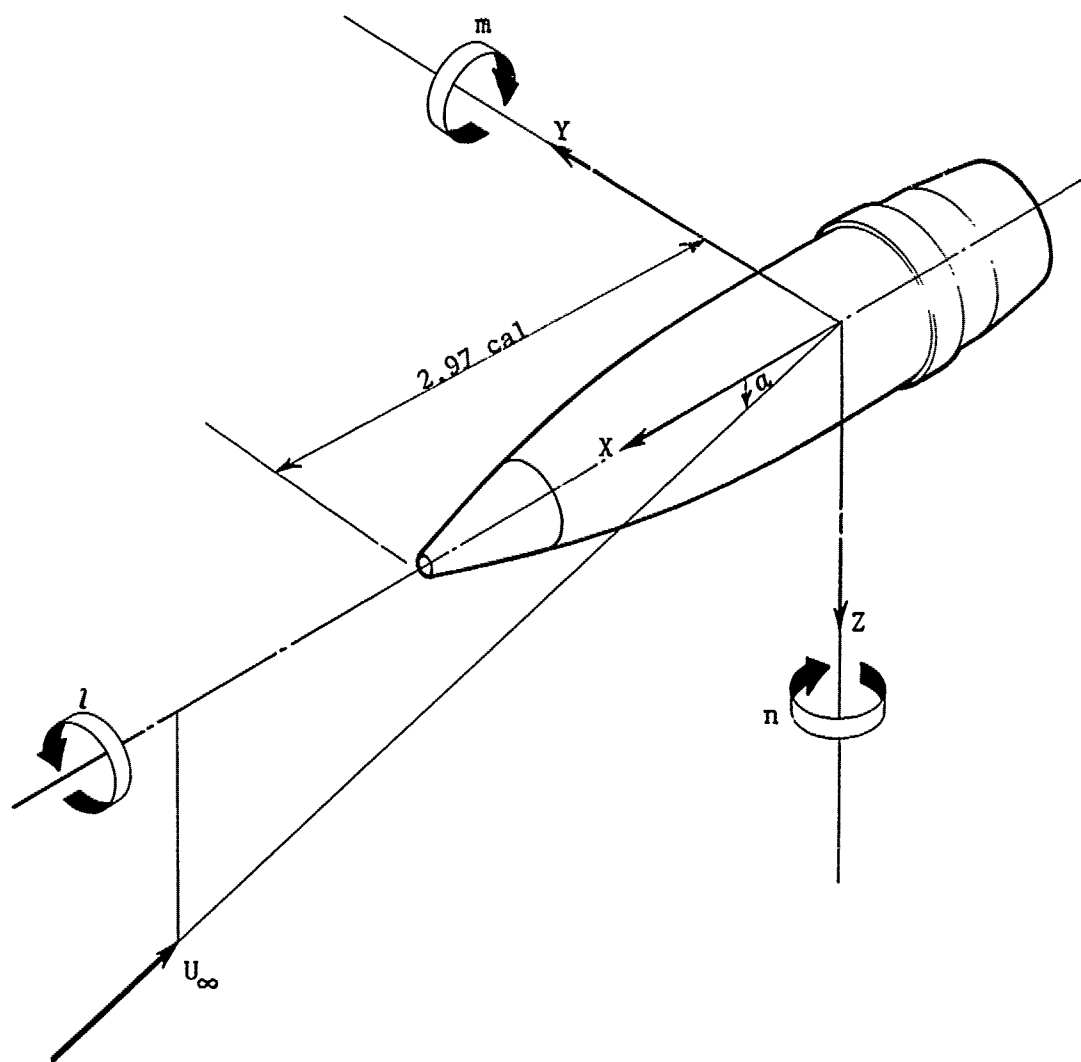
Figure 3. Axis system used in presentation of results

WSRL-0090-TR
Figure 4

(a) Non-rolling
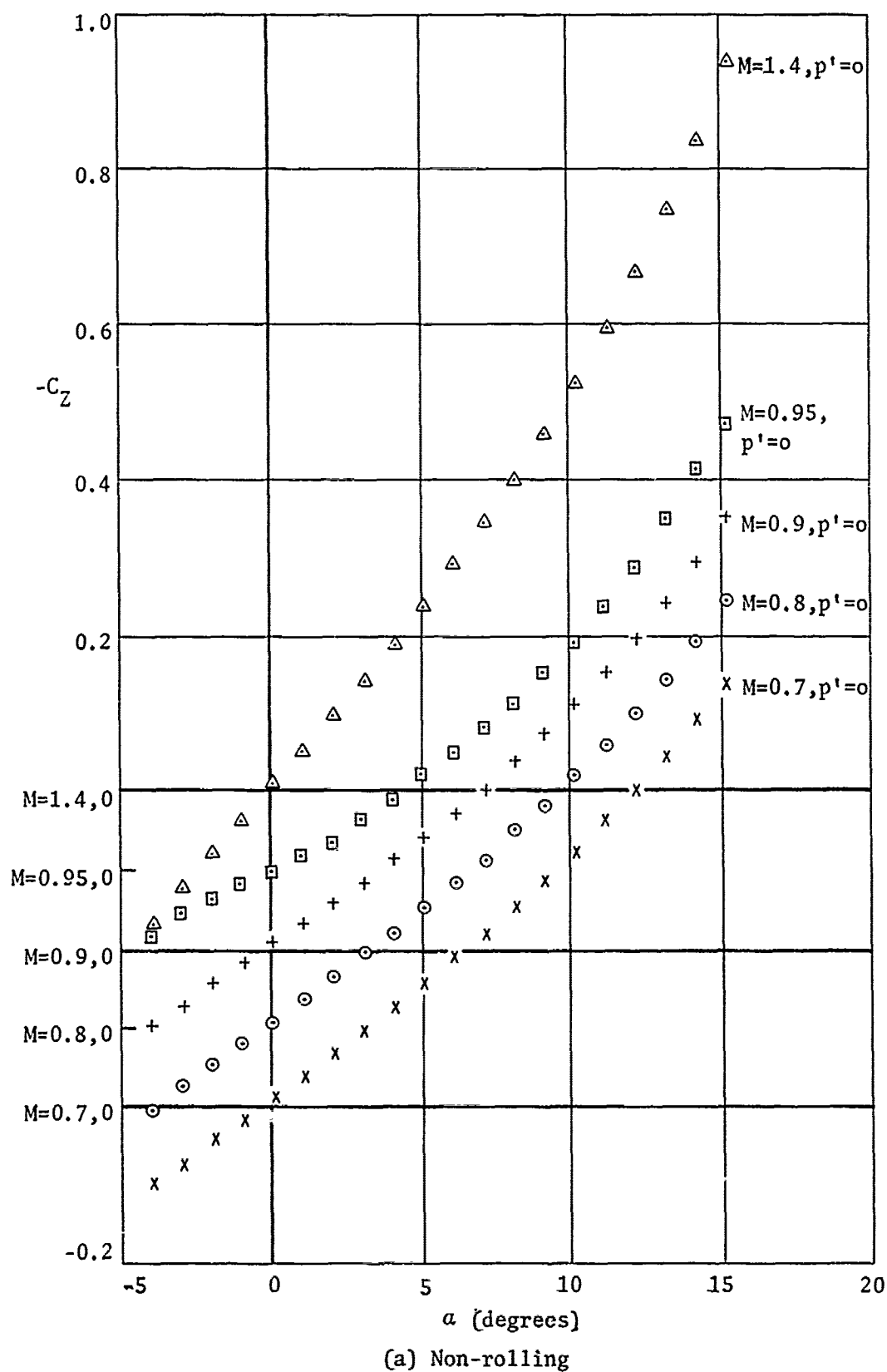
Figure 4.   Variation of normal force coefficient
with incidence, Mach no. and roll rate
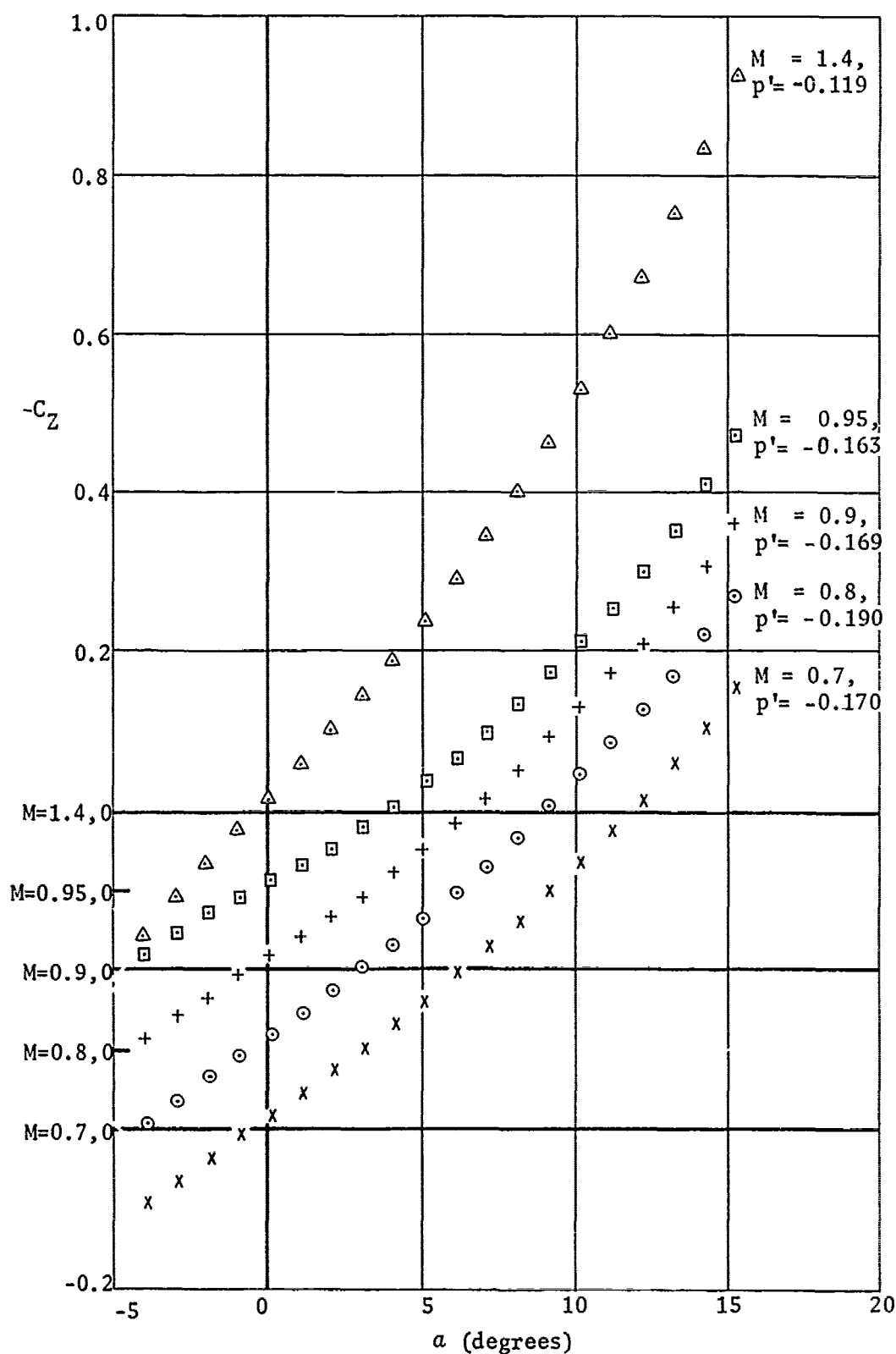
(b) Rolling - rates as shown

Figure 4(Contd.). Variation of normal force
coefficient with incidence, Mach. no. and roll rate

(a) Non-rolling
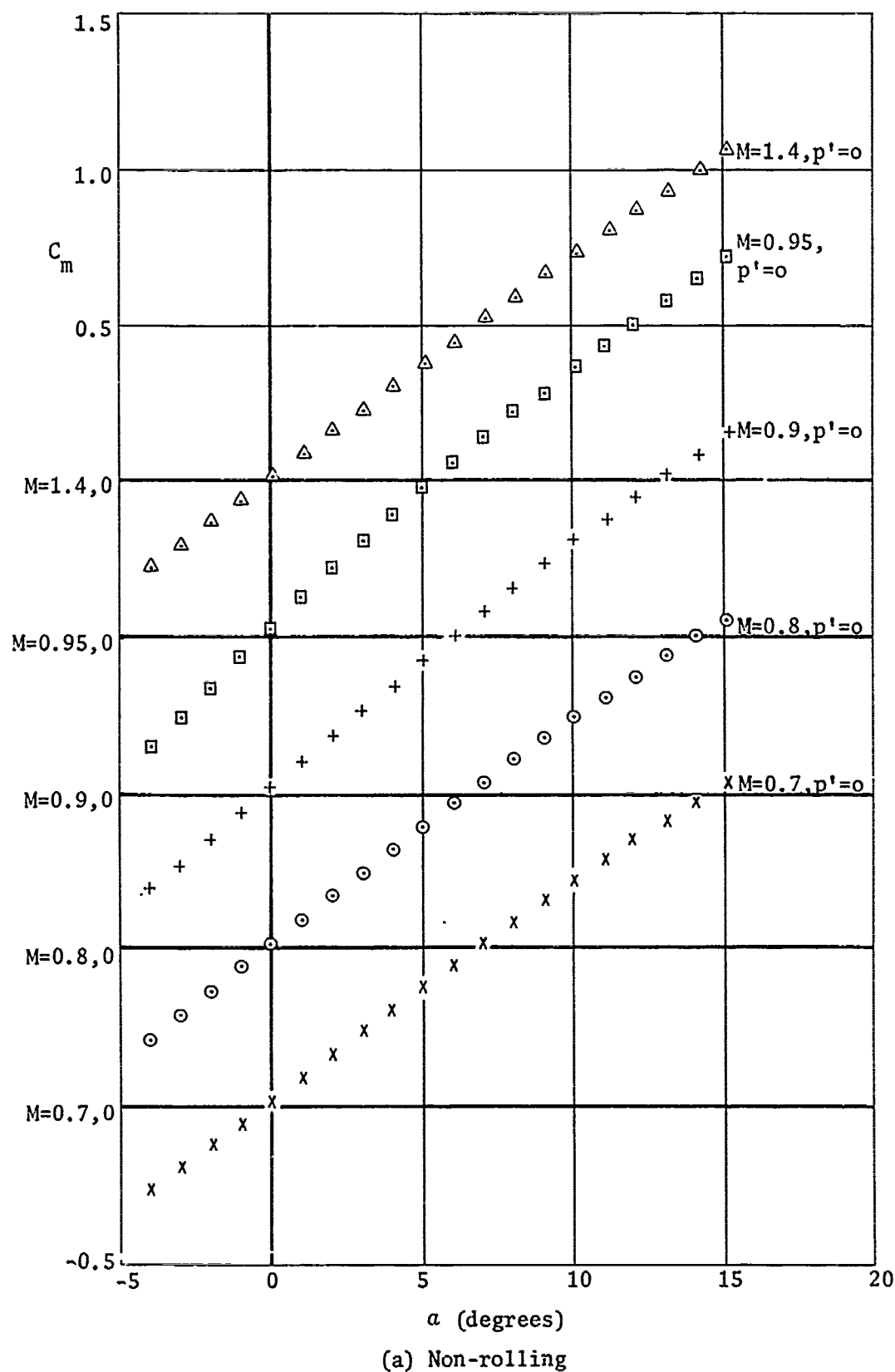
Figure 5. Variation of pitching moment coefficient
with incidence, Mach no. and roll rate

a (degrees)

(b) Rolling - rates as shown
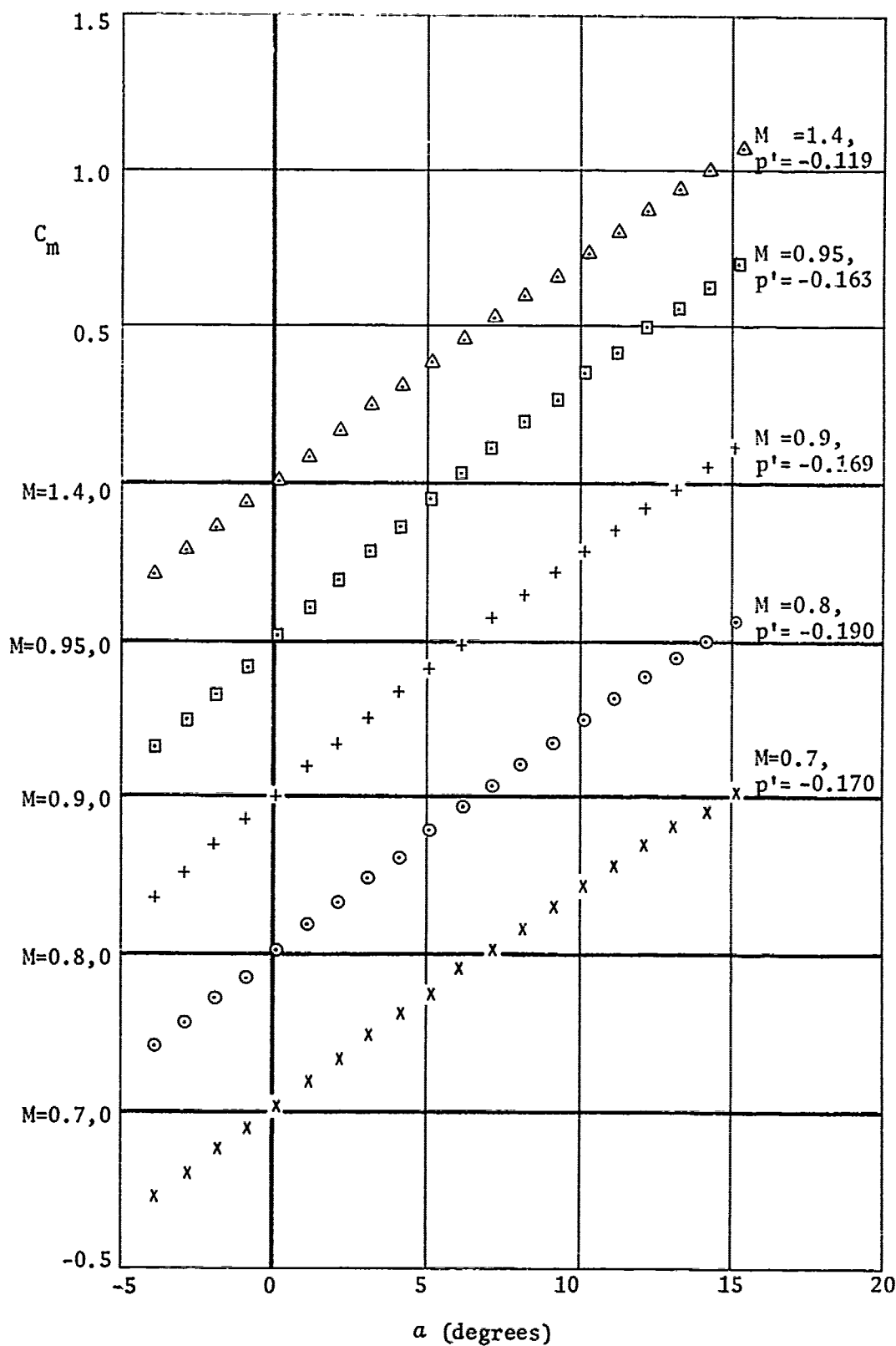
Figure 5(Contd.). Variation of pitching moment
coefficient with incidence, Mach no. and roll rate
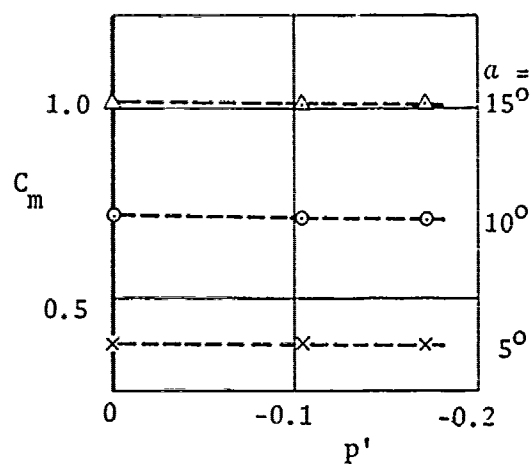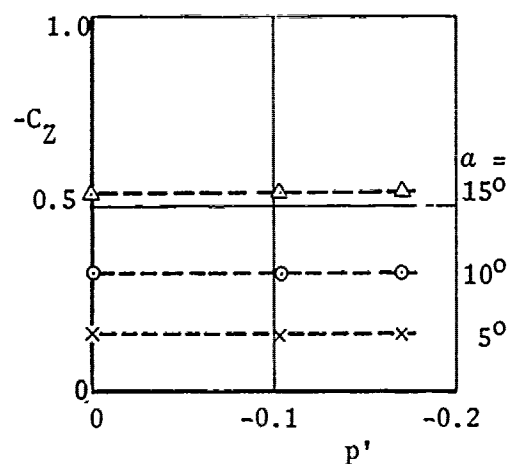
(a) M = 0.70
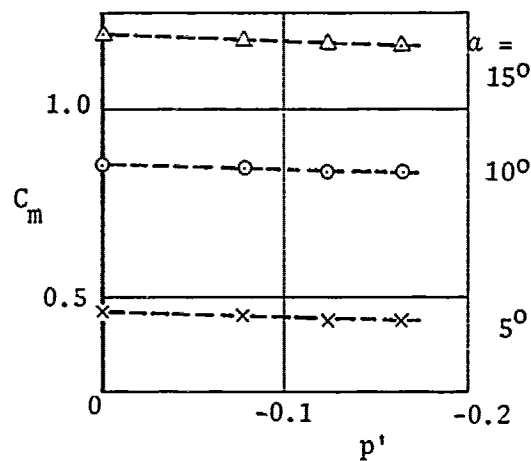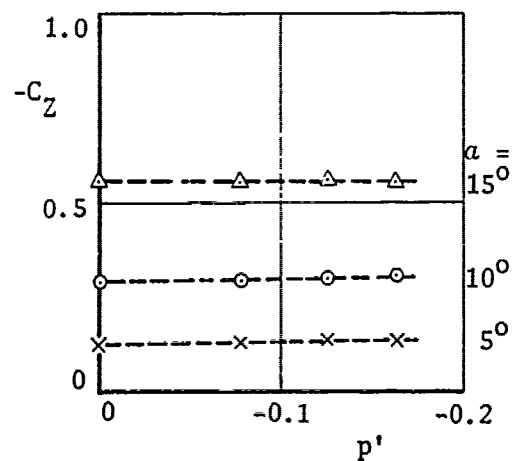
(b) M = 0.95
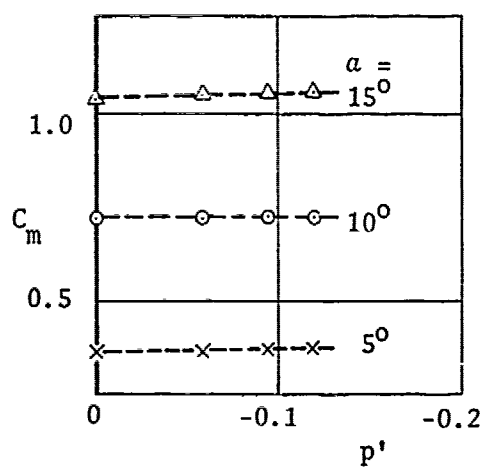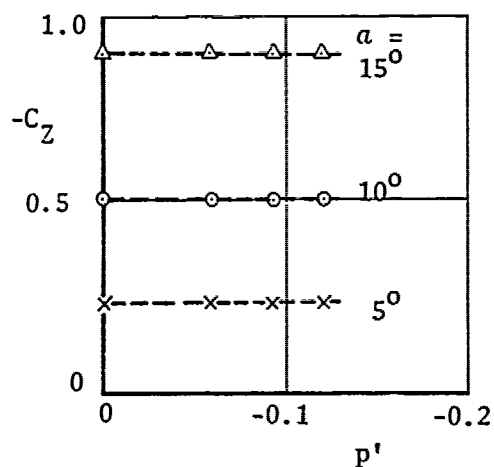
(c) M = 1.4

Figure 6.   Effect of roll rate on normal
force and pitching moment coefficients

a (degrees)
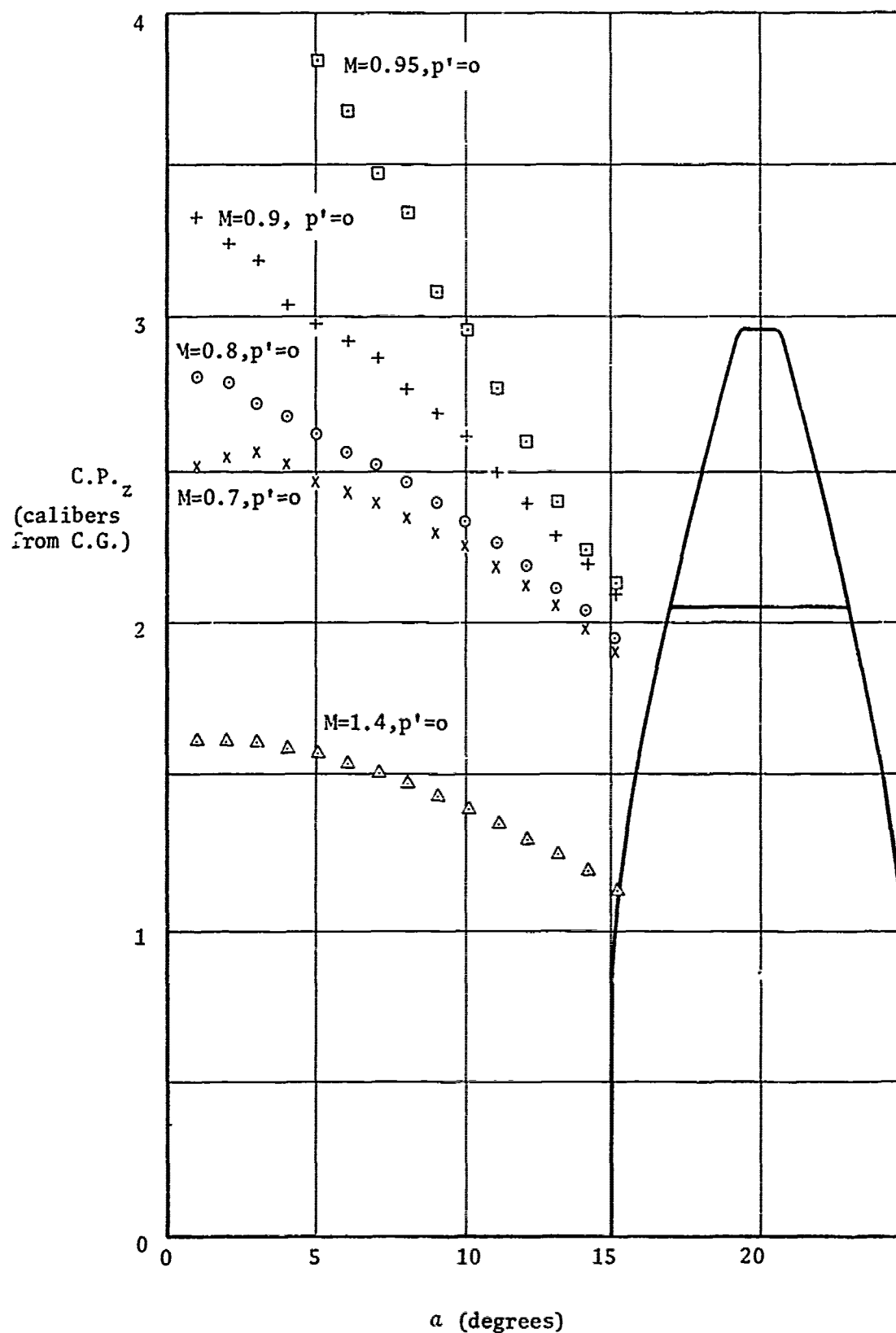
(a) Non-rolling

Figure 7. Variation of centre of pressure in pitch plane
with incidence, Mach no. and roll rate
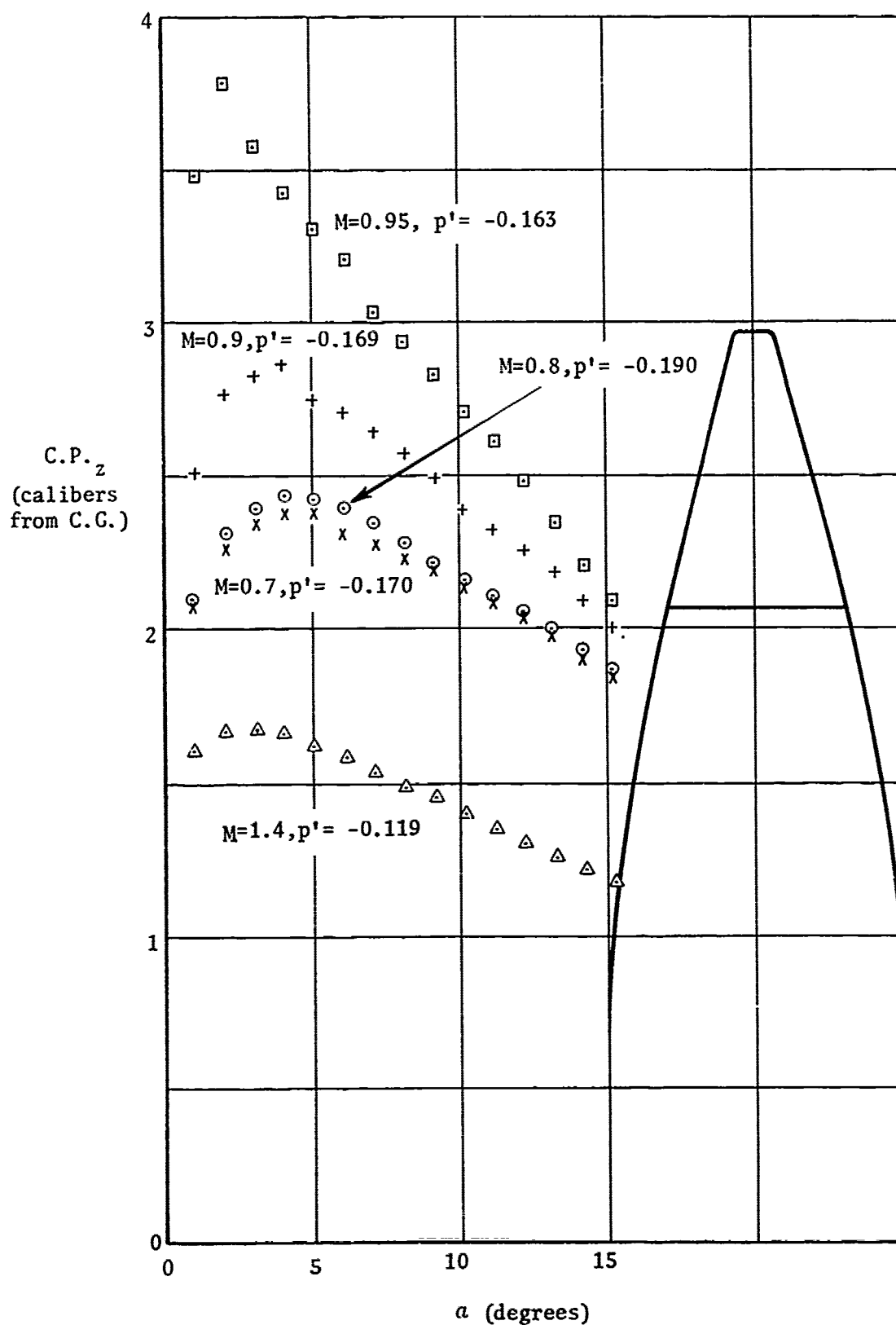
(b) Rolling - rates as shown

Figure 7(Contd.). Variation of centre of pressure in pitch
plane with incidence, Mach no. and roll rate
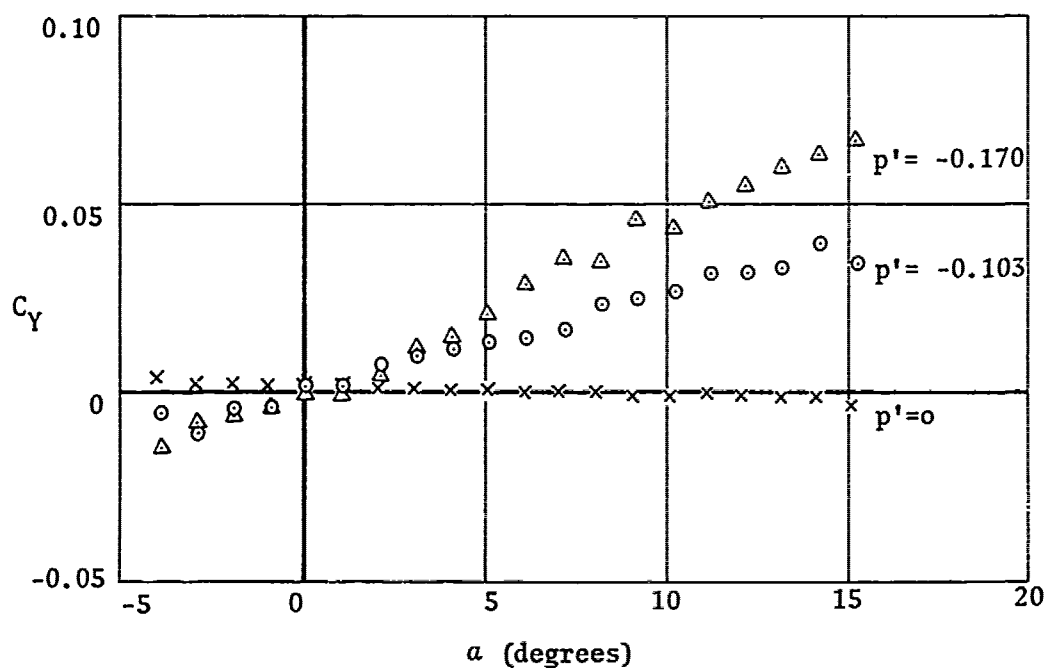
(a) M = 0.7
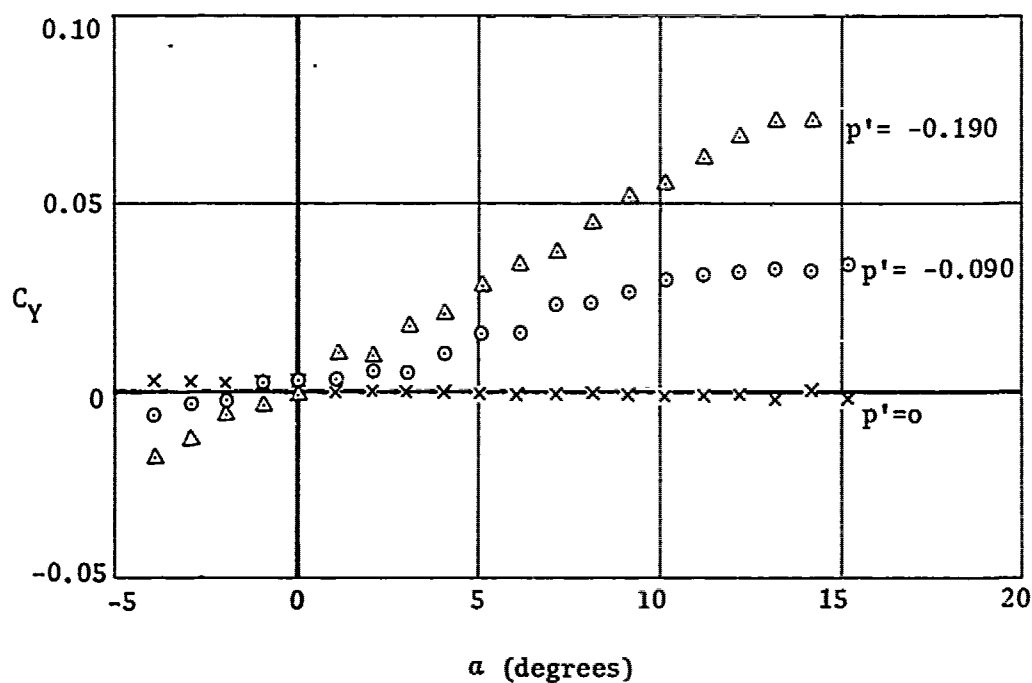
(b) M = 0.8

Figure 8. Variation of side force coefficient with
incidence, Mach no. and roll rate

(c) M = 0.9

(d) M = 0.95
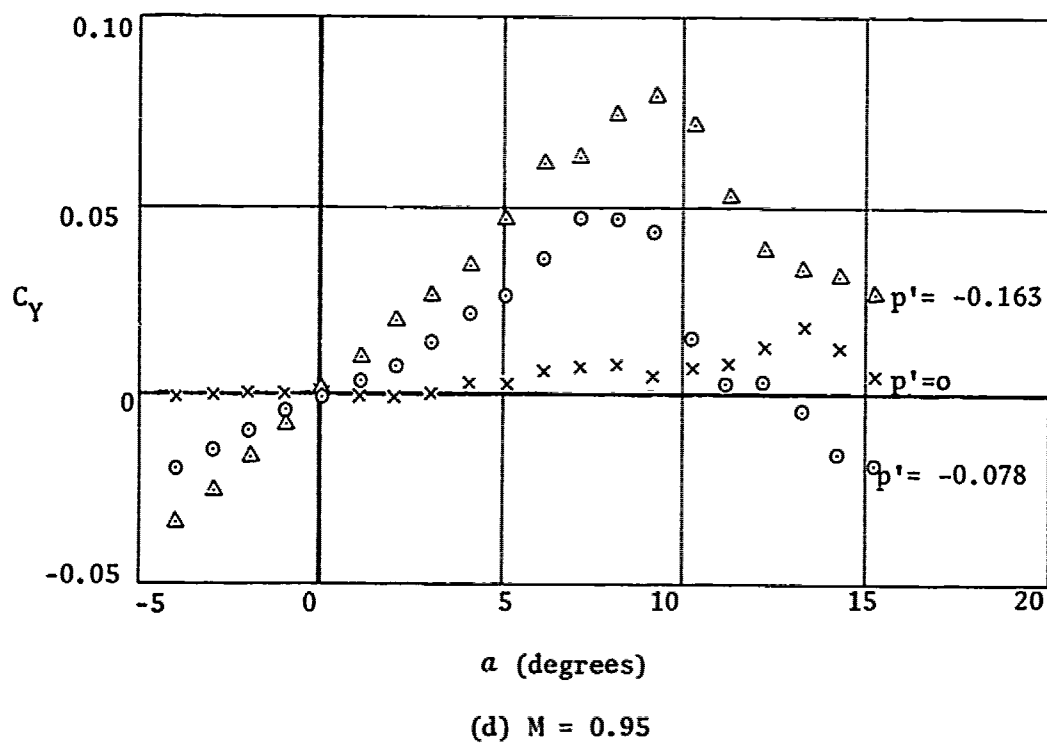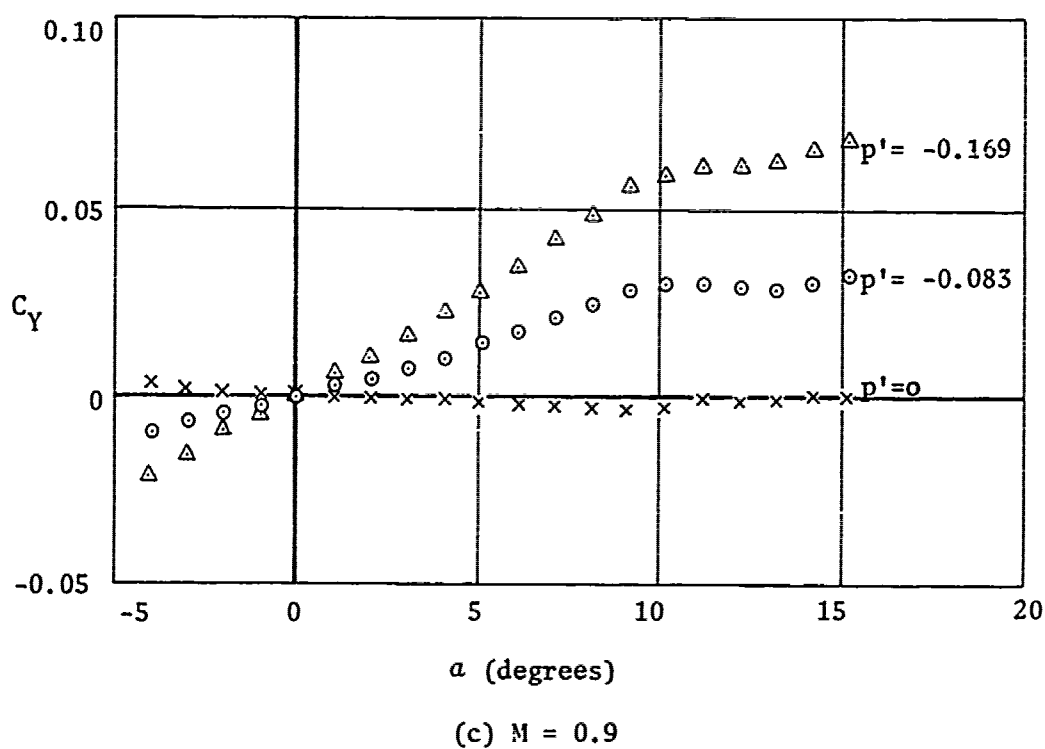
Figure 8(Contd.).   Variation of side force coefficient with
incidence, Mach no. and roll rate

(e) M = 1.4

Figure 8(Contd.).   Variation of side force coefficient with
incidence, Mach no. and roll rate

(a) M = 0.7

α (degrees)

(b) M = 0.8

α (degrees)
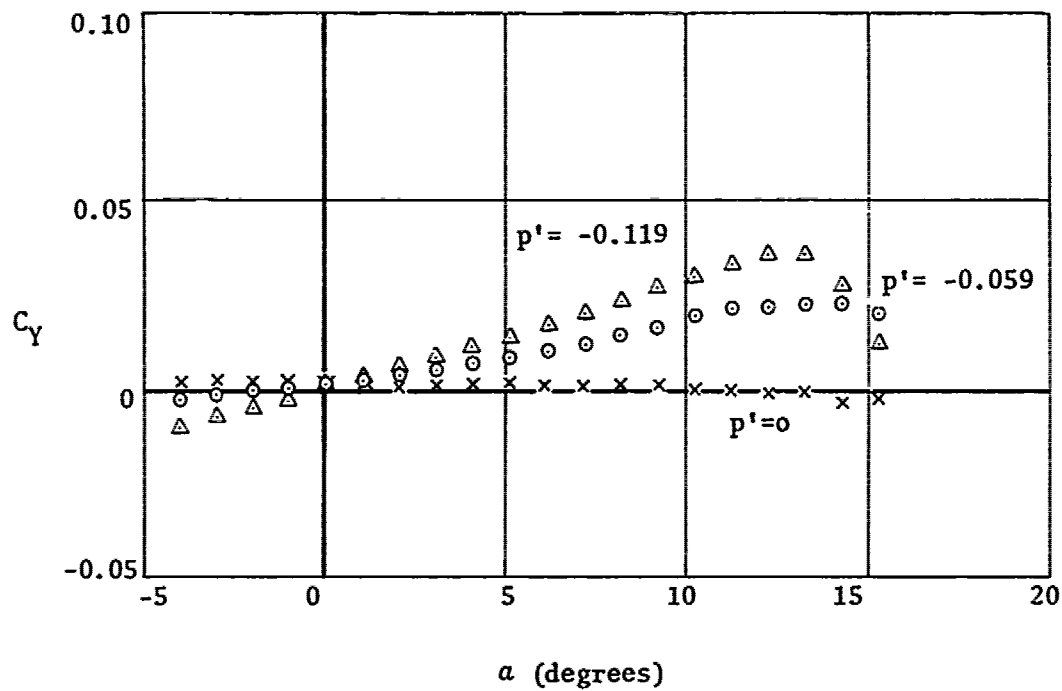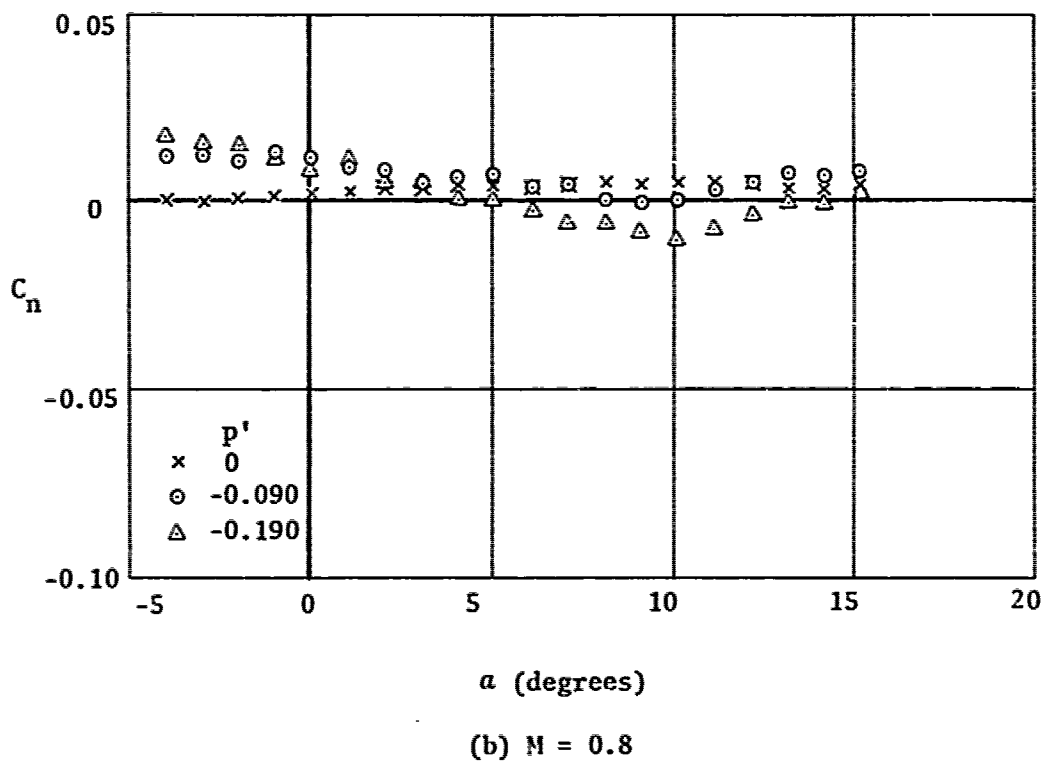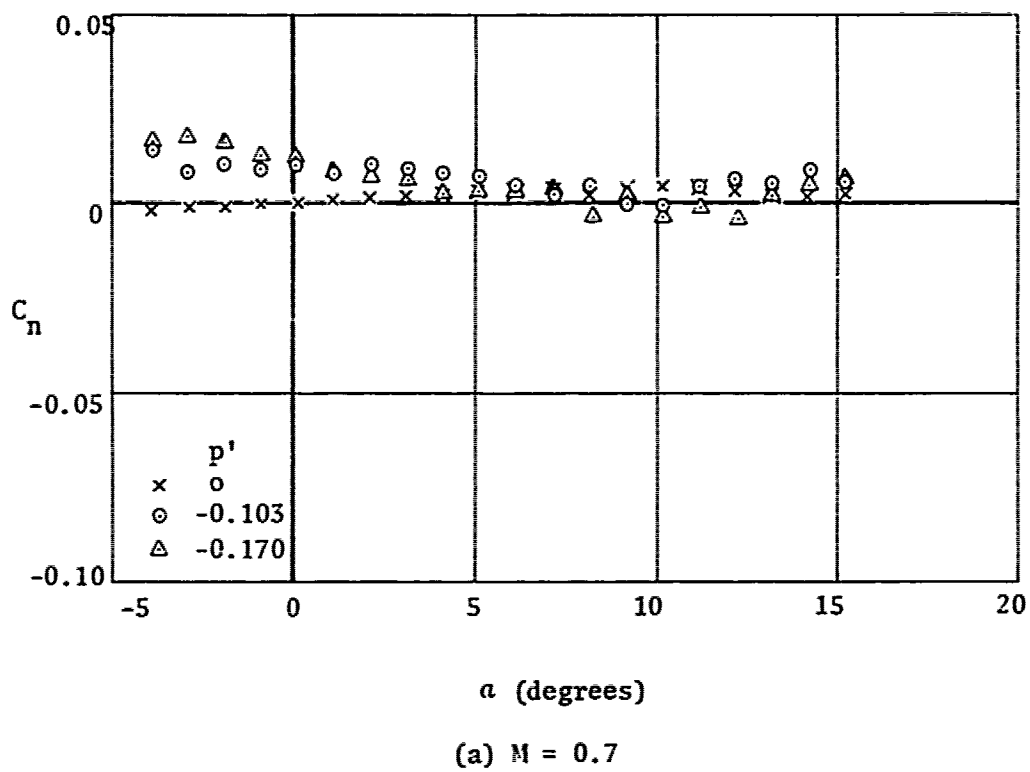
Figure 9. Variation of yawing moment coefficient with incidence,
Mach no. and roll rate
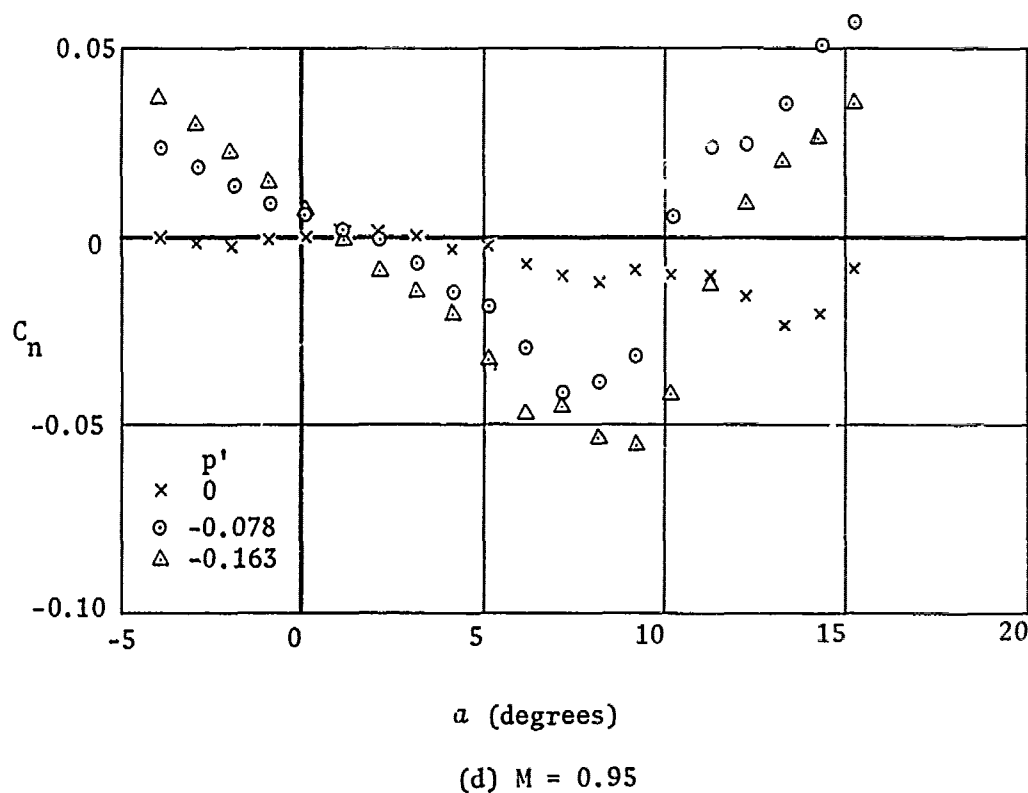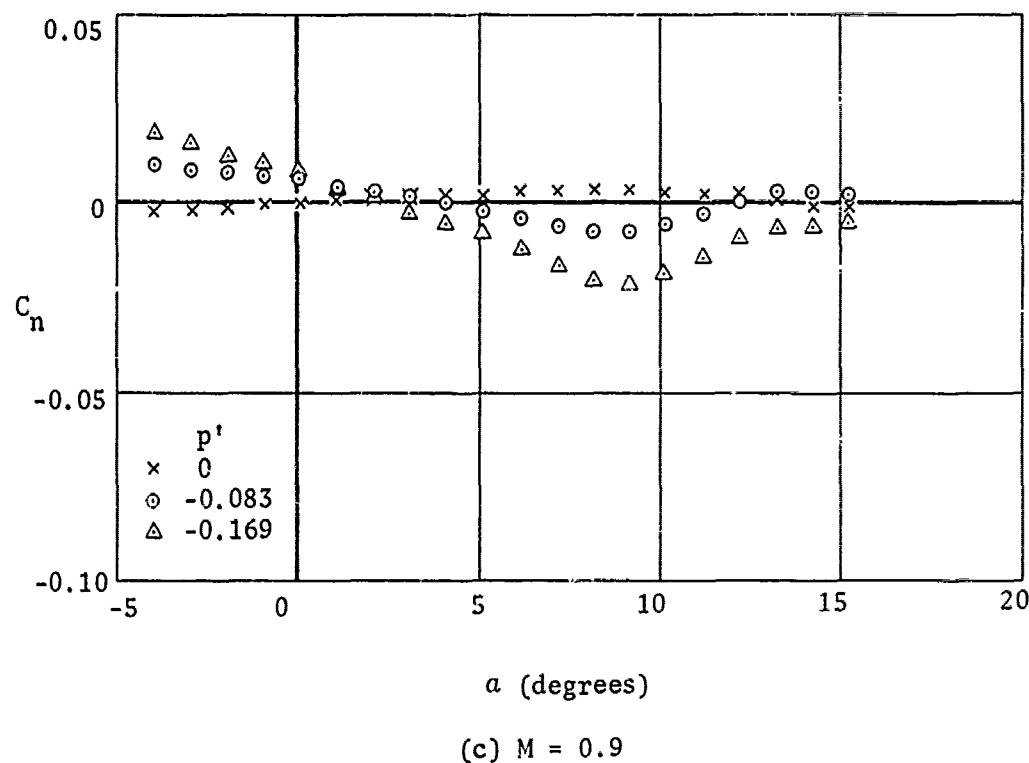
(c) M = 0.9

(d) M = 0.95

Figure 9(Contd.). Variation of yawing moment coefficient with
incidence, Mach no. and roll rate
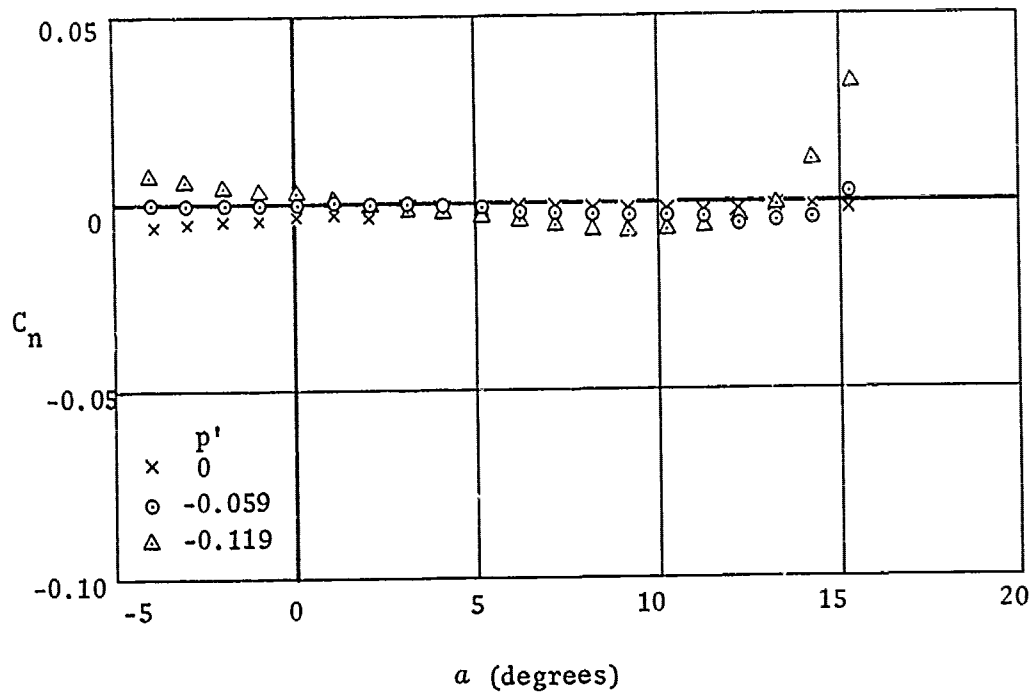
(e) M = 1.4

Figure 9(Contd.).   Variation of yawing moment coefficient with
incidence, Mach no. and roll rate

(a) C_{Za}

(b) C_{ma}
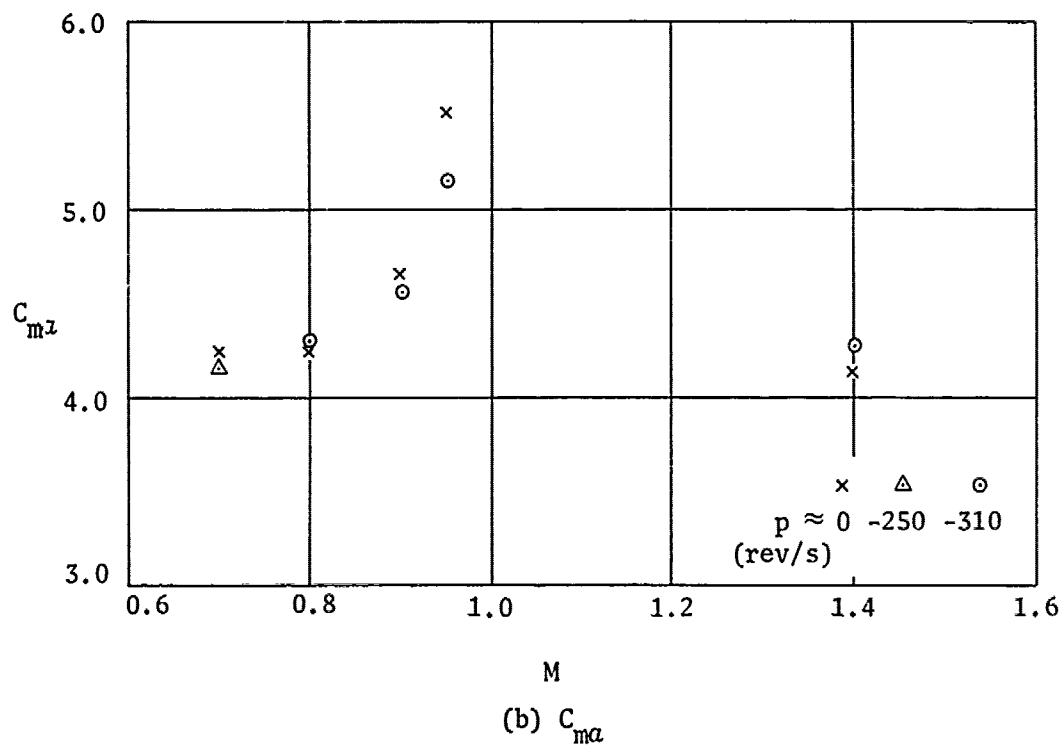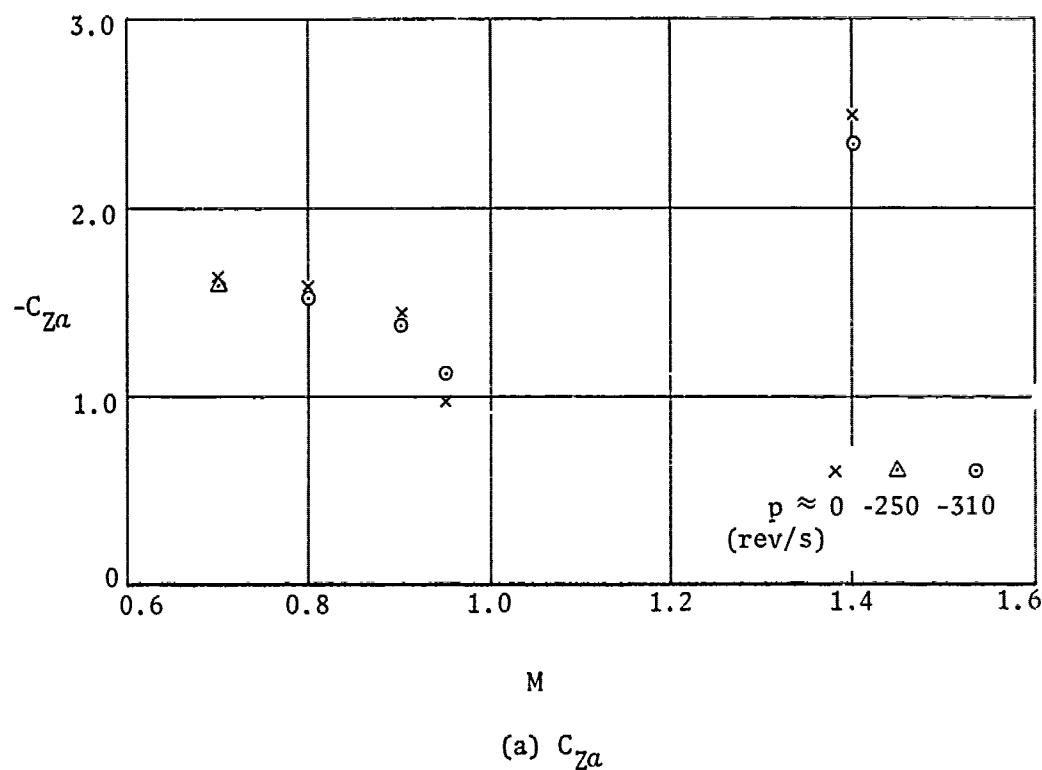
Figure 10. Variation of C_{Za}, C_{ma}, $C_{Y_{pa}}$ and $C_{n_{pa}}$ with
Mach no. and roll rate, at $a = 0^{o}$

(c) $C_{Y_{p\alpha}}$
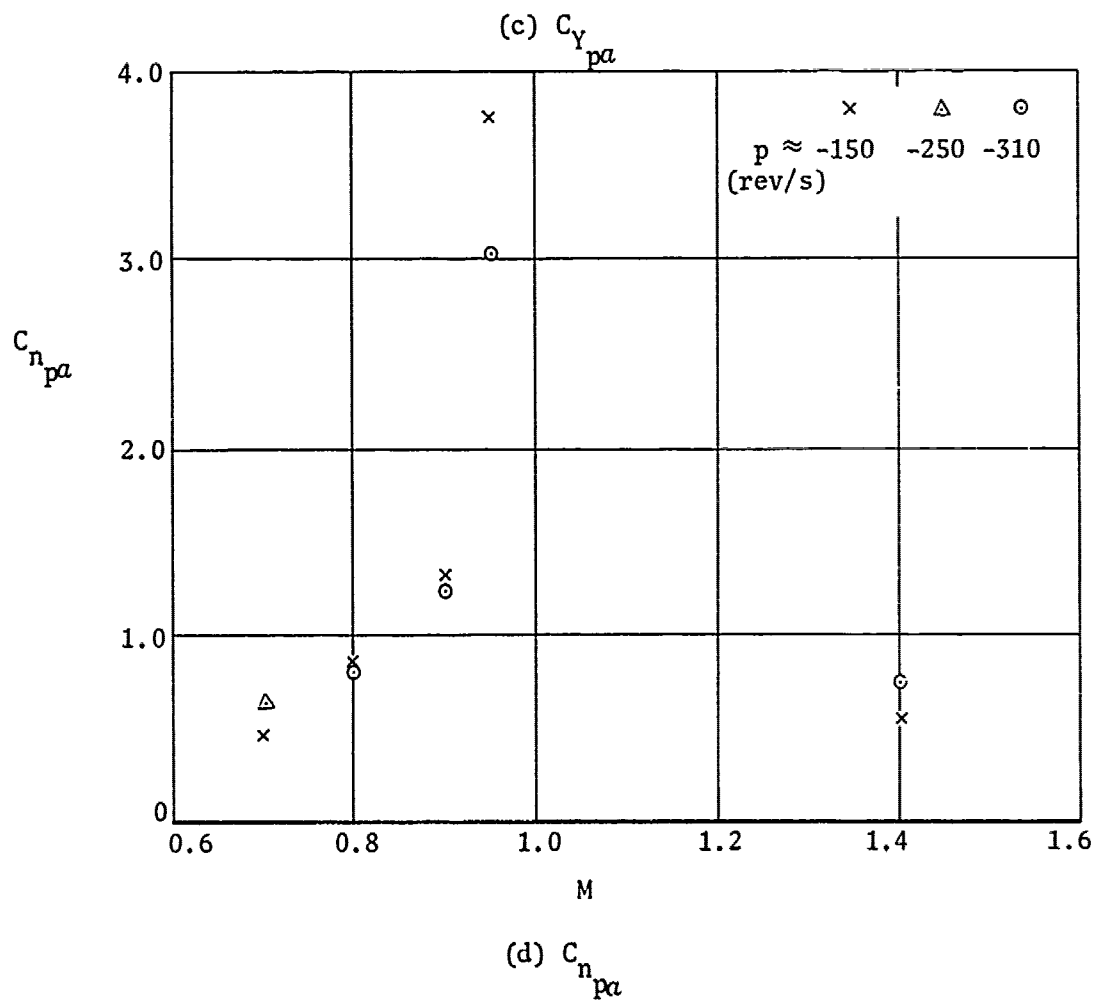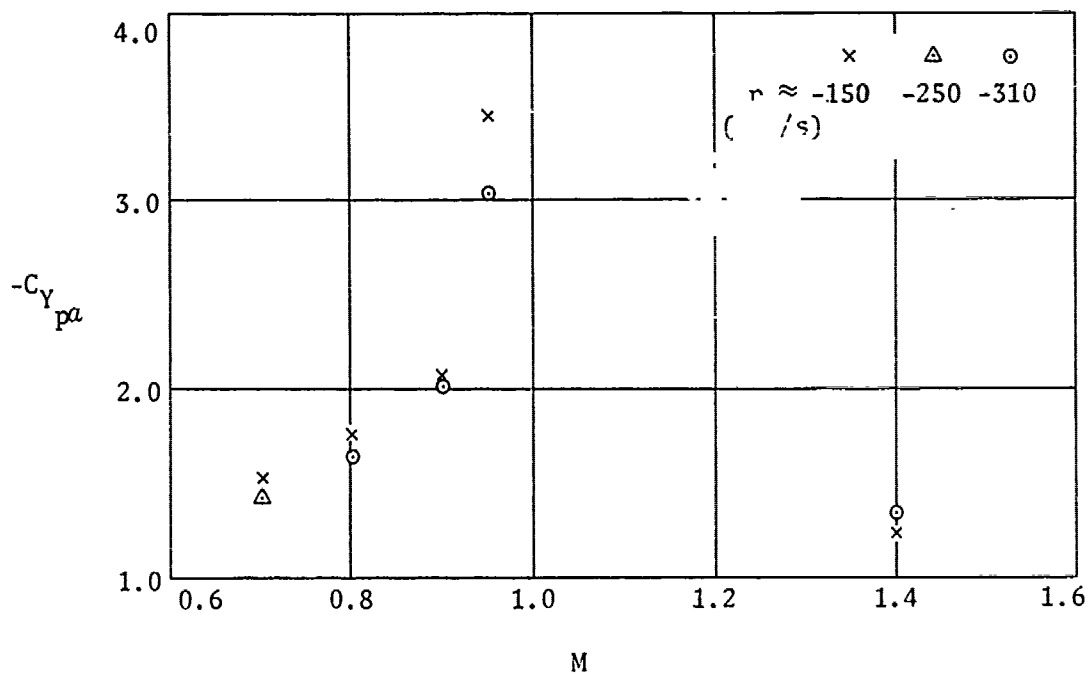
(d) $C_{n_{p\alpha}}$

Figure 10(Contd.). Variation of $C_{Z\alpha}$, $C_{m\alpha}$, $C_{Y_{p\alpha}}$ and $C_{n_{p\alpha}}$ with

Mach no. and roll rate, at $\alpha = 0^{o}$

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